ENERGY CONSERVATION IN COMMINUTION OF INDUSTRIAL MINERALS

The SNC Group

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Re: Study on Energy Conservation in the Industrial Minerals Processing Sector, Comminution: Crushing and Grinding

Dear Mr. Sirois:

We are enclosing final report in twenty five (25) copies which has been previously approved by you.

Yours truly,

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STUDY ON ENERGY CONSERVATION

IN

THE INDUSTRIAL MINERALS PROCESSING SECTOR

COMMINUTION: CRUSHING AND GRINDING

FINAL REPORT

BY

TECHNICAL DEVELOPMENT DEPARTMENT

SURVEYER, NENNIGER & CHÊNEVERT INC.

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SUMMARY

The energy conservation in the industrial minerals processing sector comminution can be achieved in a number of ways. The potential of energy conservation rests on a proper selection of machinery, the control on the input characteristic of the feed and the definition of the finished product requirements. As the constrains differ from industry to industry, the optimization of the components to conserve energy in the industrial processing sector comminution requires that proper selection of machinery be made for specific industry.

Some basic rules are applicable to the optimization of comminution circuits. These rules require that the installed machinery power be fully utilized and that the feed supplied is homogeneous and continuous. Futhermore, because the specific power consumption for crushing is lower than that for grinding, it would therefore reduce the overall energy consumption in a comminution circuit if the range of the crushing is increased. This will result in the improvement of specific power consumption because of reduction in the grinding. Furthermore, the application of process control over the entire comminution process would yield appreciable savings in the energy consumption provided the operating parameter of a given installation is known and defined.

The conventional energy-related laws have proved to be insufficient to predict the results of complex comminution operations. Mathematical models used to simulate the elements of comminution have yielded encouraging results. Simulation techniques, in conjunction with scaled-up operating data of "in production" comminution processes, are likely to advance the method of predicting the final results greatly.

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1.0 INTRODUCTION

1.0 INTRODUCTION

Since 1973, mankind has traveled from a bygone world of bountiful low-cost energy to a world of complex high-cost energy. We must adjust to this drastic change in the years immediately ahead. Early introduction of innovative, less energy intensive yet practical technologies is mandatory. It was the harnessing of energy which took man from the Stone Age to the Metal Age with the accompanying vast improvement in his living standards.

Energy, resources and the environment are inextricably interwoven and conservation of energy in mineral processing industry will have direct bearing on the improvement of standard and quality of life of mankind.

This study entitled "Energy Conservation in Industrial Minerals Processing Sector Comminution: Crushing and Grinding" is sponsored by CANMET.

The work essentially consists of compilation of certain data relating to the optimization of comminution both in terms of specific power consumption, kWh/t and in terms of processing energy consumption.

This study is carried out with the main objective to aid in the conservation of energy in the industrial mineral processing sector. It includes:

- Review of comminution technology as applied to industrial minerals taking into consideration optimal comminution limit of each phase, finished product parameters, equipment used.
- Examination of various aspects of comminution circuit control technology taking into consideration the use of computer, closed loop and automatic sampling controls.
- Outline of the requirements and specifications of the major processor and users of industrial minerals as they relate to these particular properties influenced by comminution and classification.

1.0 INTRODUCTION (cont'd)

- Based on the above, identify the optimal comminution system or processes in terms of total energy consumption.

Many industries use industrial rocks and minerals, and comminution is an important step by which raw materials are converted into final products.

An analysis of Statistics Canada data shows that, though many industries such as food and agriculture, paint and pharmaceutical industries also make an important use of industrial minerals involving size reduction at some stage, it remains that industries related to the construction sector are the most extensive users of fragmented rocks.

2.0 INDUSTRIAL MINERALS AND MAJOR RELATED INDUSTRIES

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2.0 INDUSTRIAL MINERALS AND MAJOR RELATED INDUSTRIES

The raw materials of value extracted from the earth in order to carry on industrial activities include metal and metallic ores, mineral fuels, ground water, and a large number of substances that do not fall in any of these categories.

This last group, the industrial rocks and minerals are the subject of this study.

The classification method proposed by Robert L. Bates [1] seems to be the most industry-oriented one, which corresponds to the subject treated in this paper. Two groups presented are:

- Industrial Rocks:

  Igneous rocks: Granite ; Basalt and Diabase ; Pumice and Pumicite

  Metamorphic Rocks: Slate ; Marble

  Sedimentary Rocks: Sand and Gravel ; Sandstone ; Clay ; Limestone and Dolomite ; Phosphate Rock ; Gypsum and Salt

- Industrial Minerals:

  Igneous Minerals: Nepheline syenite ; Feldspar ; Mica ; Lithium minerals ; Beryl

  Vein and Replacement Minerals: Quartz crystal ; Fluorspar ; Barite ; Magnesite

  Metamorphic Minerals: Graphite ; Asbestos ; Talc ; Vermiculite

  Sedimentary minerals: Diamond ; Diatomite ; Potash minerals ; Sodium minerals ; Borates ; Nitrates ; Sulfur.

2.0 INDUSTRIAL MINERALS AND MAJOR RELATED INDUSTRIES (cont'd)

The most important of these raw materials are described in detail in Appendix A; these are: Asbestos - Barite - Gypsum - Limestone - Dolomite - Potash - Salt - Sand and Gravel - Sulphur.

The construction industry consumes about half of the total output in value and much more in tonnage, in the form of crushed stone, dimension stone, and the raw materials for cement, brick and title. Sulfur, salt and limestone are basic to the chemical industry. Agriculture depends on phosphates, nitrates, potash and lime. Clay supplemented by feldspar, talc and other minerals supports the ceramics industry.

Limestone and fluorspar are necessary to the industry in the processing of the iron ore. Metallurgical process requires graphite, magnesite, molding sand and fire clay.

Other rocks and minerals are used for abrasives, electrical insulation, oil well drilling muds, filtration media and lubricants.

For 1979, the latest data,supplied by Statistics Canada, point out the six leading products based on their production value:

	POTASH	CEMENT	ASBESTOS	SAND/GRAVEL	STONE	SULFUR
dollars, 10^6	735.2	653.9	607.5	457.1	330.7	159.6
tonnes, 10^6	7.1	11.8*	1.5	285.2	109.7	6.3

Table 1 gives a breakdown of the 1979 Canadian production[29].
Table 10 summarizes the main characteristics of the industrial rocks and minerals along with the related industries.

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* 11.8 million tonnes of cement correspond approximately to 17.9 million tonnes of raw materials such as limestone and clay.

3.0 COMMINUTION

3.0 COMMINUTION

Comminution is normally the first step in beneficiation of solid minerals. It is usually a stage process, utilizing in the successive steps, machines especially suitable for reduction of particle sizes. The stages starting with the rocks as mined or quarried and comprising successive reduction steps down to a final stage employed for production of finest sizes are called crushing. Traditionally, coarse crushing includes crushing operations discharging at sizes 4 to 6"; intermediate crushing comprises operations taking feeds 6 or 8" maximum and making products down to ½ or 3/8"; fine crushing is reduction by crushing to ¼" or fines. The distinctions are not sharp. Reduction below this range falls under the classification of grinding.

In fact, when the purpose of comminution is a size reduction of the mined minerals only to get a single final product, the crushing operation is performed in not more than two stages. When intermediate product(s) are also produced by the plant, then the crushing operation is subdivised in many stages. Another reason to crush the raw material in several stages is the need for delicate separation/classification operation between two crushing stages.

The grinding operation in all cases constitutes the final stage of comminution. In general, the output product should offer the ultimate characteristics of a final product which is essentially the fineness i.e. the specific area of the particles.

3.1 General

The purpose of reducing the size of solid particles are the results of the following concepts:

3.0 COMMINUTION (cont'd)

3.1 General (cont'd)

- Miner concept (16): To liberate valuable minerals from waste prior to concentration. The extent to which breakage must proceed depends on the size of the valuable particles. This particle dimension is not an intrinsic parameter to the concerned mineral, but may vary according to the ore and the characteristics of the ore deposit. The treatment of the asbestos ore may constitute a good example. Asbestos, found in veinlets, mostly less than an inch width, must be separated of its massive serpentine walls.

- Chemist concept: To generate surface area in order to facilitate chemical reactions; the latter being directly proportional to the exposed surface of the particle. One of the best examples may be found in the cement manufacturing, combinations of the lime with the silica, iron and alumina oxides in the rotary kiln. The fineness of the cements as finished product, will dictate the intensity of hydration which determines the performances of the mortar or concrete.

- Civil contractor concept: To produce mineral particles or dimension stone of required size or shape. A good illustration is supplied by the aggregate used in the construction industries. Aggregate should conform with well defined granular distribution constraints both in concrete and road building in general. The content of fines is severely limited.

3.2 Crushing principles

Crushing is a mechanical operation in which a sufficient force is applied to relatively brittle solid particles in such directions that failure of the bonding forces in the particles is brought about.

3.0 COMMINUTION (cont'd)

3.2 Crushing principles (cont'd)

The four basic ways to reduce a material are: by impact, attrition, shear or compression. Most crushers employ a combination of these crushing methods.

Impact:

Impact refers to the sharp, instantaneous impingement of one moving object against another. Both the objects may be moving or one object may be motionless. There are two variations of impact: gravity impact and dynamic impact. Coal dropped onto a hard surface such as a steel plate is an example of gravity impact. Gravity impact is most often used when it is necessary to separate two materials which have relatively different friability. The more friable material is broken, while the less friable material remains unbroken. Separation can then be done by screening. Material dropping in front of a moving hammer illustrates dynamic impact. When crushed by dynamic impact, the force of impact accelerates movement of the reduced particles toward breaker blocks and/or other hammers. Dynamic impact has definite advantages for the reduction of many materials:

- When a cubicle particle is needed.
- When finished product must be well graded and must meet intermediate sizing specifications as well as top and bottom specifications.
- When ores must be broken along natural cleavage lines to free and separate undesirable inclusions.
- When materials are too hard and abrasive for hammer mills but where jaw crushers cannot be used because of particle shape requirements, high moisture content or capacity.

3.0 COMMINUTION (cont'd)

3.2 Crushing principles (cont'd)

Attrition:

Attrition is a term applied to the reduction of materials by scrubbing it between two hard surfaces. Hammer mills operate with close clearances between the hammers and the screen bars and they reduce by attrition combined with shear and impact reduction. Though attrition consumes more power and exacts heavier wears on hammers and screen bars, it is practical for crushing the less abrasive material such as pure limestone and coal. Attrition crushing is most useful in the following circumstances:

- When material is friable or not too abrasive
- When a closed-circuit system is not desirable to control top size.
- When a maximum of fines is required.

Shear:

Shear consists of a trimming or cleaving action than the rubbing action associated with attrition. Shear is usually combined with other methods. Shear crushing is normally called for under the following conditions:

- When material is somewhat friable and has a relatively low silica content.
- For primary crushing with a reduction ratio of 6 to 1.
- When a minimum of fines is desired.
- When a relatively coarse product is desired (no finer than $1\frac{1}{2}$" top size).

3.0 COMMINUTION (Cont'd)

3.2 Crushing principles (cont'd)

Compression:

Crushing by compression is done between two surfaces, with the work being done by one or both surfaces. Jaw crushers using this method of compressions are suitable for reducing extremely hard and abrasive rock. However, some jaw crushers employ attrition as well as compression and are not suitable for abrasive rock since the rubbing action accentuates the wear on crushing surfaces. Compression is used as follows:

- If the material is hard and tough
- If the material is abrasive
- If the material is not sticky
- When a uniform product with a minimum of fines is desired
- When the finished product is to be relatively coarse, i.e. $1\frac{1}{2}$" or larger top size
- When the material will break cubically.

3.3 Grinding Principles

Grinding is powdering or pulverizing by pressure and abrasion. Since fine powder is the desired product it follows that in most cases the comminuting equipment should be integrated in a system to apply the necessary forces. Hence one definition of a grinding machine is that it is a crushing machine in which the crushing elements touch except in so far as they are prevented from doing so by the material being broken[30].

Production of surface is an important element in the griding of most nonmetallic minerals, the purpose being to prepare the material for uses in which chemical reaction of some kind is involved.

3.0 COMMINUTION (cont'd)

3.3 Grinding principles (cont'd)

In fine comminution the size characteristics of the ground product are determined, other things being equal, by the way in which the particle was reduced in size. In general, shear loading (abrasion) and impact work are more productive of fines than gradual loading. Also, some device is always used to hinder escape of unground material from grinding zone.

Grinding may be performed either in wet process or in dry process, in open or closed circuit. The primary factors that determine whether a material is to be ground wet or dry are numerous. Some of them are listed here below:
Wear rate, tendancy to pack or slick, corrosive effect - Particle distribution quality of the finished product - Relative economic efficiency of the operation as such or as a component of the entire mineral beneficiation process.

The choice between an open or a closed circuit is mainly governed by economics. Further a controlable particle size distribution of the ground material is also to be taken into consideration in the choice.

3.4 Theories of Comminution

3.4.1 Particles size distribution laws

All comminution equipment provide invariably a product with a granulometry more or less widely spread. The required particle size fraction is always accompanied by undesirable fractions beyond the size range required.

3.0 COMMINUTION (cont'd)

3.4 Theories of Comminution (cont'd)

3.4.1 Particles size distribution laws (cont'd)

The distribution of particles of any given dimension are graphically represented to give what is called particle size distribution curves or granulometric curves.

The shape of the curves varies significantly between two products. It depends mainly on the type of comminution and circuit used, and on the mechanical properties of the feed. Also it is related to the magnitude of required size reduction. For example, the same material ground by different means to the same fineness expressed as specific surface value or sieve residue will produce two quite different curve shapes.

The current representation of the particle size distribution is shown in Fig. 1.

Many attempts have been made to relate the entire particle size distribution of a given ground product to the knowledge of one or two parameters only, such as global specific surface or residue at a given sieve aperture through break up.

o Gaudin - Schumann Equation:

$$P_d = 100\ (d/do)^n$$

when d_o = dimension corresponding to 100% passing

P_d = % of passing at a given dimension, d.

In logarithmic representation, the equation gives a straight line with a slope n. However, at P_d values of 80 or more, the Gaudin-Schumann law does not hold true.

3.0 COMMINUTION (cont'd)

3.4.1 Particles size distribution laws (cont'd)

- Rosin - Rammler Equation

$$R_d = 100\, e^{-(d/d_o)^n}$$

where R_d = % of residue of a given dimension, d

d_o = dimension corresponding to 36.8% residue

The rosin - Rammler equation is graphically representated by a log scale on the X axis (particle size) and a log log scale on the Y axis (residue). Here again, the law does not always hold true for the whole granular distribution and applies only for 50 micron particles and below. (See figure 2).

- Other Formulae

Other formulae have also been proposed but they are rarely used.

- Gaudin - Mely - Schumann

$$Y = 100 - 100\left[1-\left(\frac{X}{X_o}\right)^m\right]^r$$

- Broadbent - Calcott

$$Y = 100\ \frac{1 - e^{-(X/X_o)}}{1 - e^{-1}}$$

- Gaudin - Meloy

$$Y = 100 - 100\left(1 - \frac{X}{X_o}\right)^m$$

Where Y = % of passing at a given dimension X

m and r = exponents constants

X_o = maximum sized particle

Any of the proposed laws may be considered for a universal use. Only correlations drawn from empirical data and in a given context may help in the provision of the fineness distribution and therefore in the process control.

3.0 COMMINUTION (cont'd)

3.4.2 Energy related laws

Many theories of grinding have been proposed to relate the size reduction rate to the energy required. The most often referred are:

- Rittinger's Law (1867)

  $W = k_1 (1/d - 1/D)$

This law expresses the required work to reduce a solid from a size D to size d. By this law, Rittinger suggested that the new surface area produced is proportional to the energy consumed, assuming energy requirements in terms of 100% efficient energy use.

- Kick's Laws (1885)

  $W = k_2 \, Ln \, (D/d)$

Kick took into account the size reduction ratio, regardless of the initial dimension of the solid. That means that the relative reduction in volume is obtained for constant energy input per unit. Kick's law may be applied only in crushing or coarse grinding.

- Bond's Law (1951)

Bond's Third Theory supposes that the energy needed to grind a particle from a size F to a size P is the difference between the energies required respectively to grind a material from a theoritically infinite size to the size F and then to size P.

$$W = \frac{10 \, W_i}{P^{.5}} - \frac{10 \, W_i}{f^{.5}}$$

Where

W_i: Work index of the material

3.4.2. Energy related laws (cont'd)

W_i is the measure which expresses the resistance of the material to crushing and grinding. It is determined by laboratory tests.

The Third Theory of Bond has been generally accepted by most of the world's leading mining companies, and is universally used as standards.

3.5 Laboratory testing

3.5.1 Material grindability and crushability

The determination of a factor which would reveal the characteristics of a given material to be crushed and ground is necessary for the following reasons:

- In order to predict in given circumstances and by comparison the specific power consumption on an industrial scale for the design of comminution equipment
- In order to evaluate the performances of a given installation

Many laboratory tests have been conceived. Some of them are "custom made" apparatus and are used internally by concerned laboratories. Others are more frequently encountered all over the world. The latter will be reviewed in more details.

For the determination of grindability, basically, all the laboratory apparatus may be classified into two large classes of equipment.

- Laboratory ball mills with a more or less great length/diameter ratio.
- Hardgrove type mills where the grinding is achieved by a certain number of balls running in a fixed grinding bowl.

In the first type mill, the size reduction is mostly achieved by impact whereas in the second group, the work is done by attrition.

3.5.1.1 Bond's Method:

Bond's method is the most currently accepted. The mill is a 30 cm x 30 cm cylinder, loaded at 21% of its internal volume by 20.5 kg of 1½" down to ½" spherical balls. The speed of rotation, 70 RPM, corresponds to 91% of the critical speed. The test requires a 700 cm^3 sample (approximately 1.2 kg) precrushed at 100% passing 3.15 mm.

Bond's method strives to achieve the conditions of a closed-circuit mill system, simulating a 250% circulating load by the use of a 200 Mesh sieve (75 micron) as a separator.

The grinding test is performed stepwise. After a certain number of revolutions, the undersize material (< 75 microns) is withdrawn as finished product and replaced by an equal amount of primary feed material. And so forth. The final result, expressed as W_i in kWh/t, is called Bond's Work Index.

Table 2 gives some values of work index. The determination of the Bond's Work Index was destinated first to the Bond's Third Theory formula as the constant which correlates the mechanical characteristics of the material. However, it appears today that more and more the Bond's Index is considered as such, for its "intrinsic" value and widely used for comparisons purposes, where it is proving to be very useful.

- As the Work Index is valid only for a standard mill of 2.5 m diameter operating with wet process in closed circuit, Bond gives certain correction factors for specified cases.

- Bond's grindability test is time-consuming (1 test per day).

3.0 COMMINUTION (cont'd)

3.5.1.2 Hardgrove's Method [32]

In Hardgrove's method, the test is performed in a small ball mill ring, comprising eight grinding balls of 1" diameter running in a fixed bowl and driven by a grinding ring loaded by a weight of 25 kg.

The test method is very simple; a quantity of 50g of material from 590 to 1190 microns is ground for 60 revolutions and then sieved on a 200 mesh sieve (75 microns). The passing material (D) is weighted and the grindability index deduced as per the following formula:

$$H = 13 - 6.93\ D$$

- Hardgrove's test is usually used for determining coal grindability.
- The result is purely a relative value linked to a reference substance, a well known easily grindable coal - which is assigned the grindability index H = 100. The method does not relate grindability proportionally with the actual specific work.

3.5.1.3 Zeisel's method [32]

Zeisel's apparatus is a modified version of the Hardgrove's bowl. The improvements consist in being able to grind the material to greater fineness and to measure the energy input by means of torque measurement. The sample weight is 30g, with a particle size range of 0.75 - 1.0 mm.

After a certain number of revolutions of the grinding ring, a sample is taken for fineness measurement. Grinding is then resumed. On completion of the test, a diagram is finally obtained in which the specific grinding work - grindability - is plotted against the

3.5.1.3 Zeisel's method[32] (cont'd)

specific surface. When the material is liable to stick or to agglomerate, then another procedure is applied which recalls the Bond's method, by simulating a circulating load (use of a sieve as a classifier). In this closed-circuit procedure, the degree of size reduction is the ratio of the total residue on the 90 micron sieve to the total passing the 125 micron sieve.

The Figure 4 demonstrates this well. By increasing specific surface, the specific work required for further size reduction progressively increases, in other words, the finer a material is ground, the lower becomes its grindability. This very well known phenomenon is even more clearly seen in the series of curves presented in Figure 5 when the grindability is expressed as a specific surface work namely specific surface/Wh instead of the conventional specific work, kWh/t. Depending on the material, the curves display more or less pronounced optima. This inflexion shows how important is the proper choice between the material to be size-reduced on one hand, and the comminution machinery type and the required fineness on the other hand.

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According to Zisselmar[32], laboratory results may well be applied to the industrial scale. He proposes the following formula:

$$W = 6.38\ R_{90}^{-0.165}\ W_z^{0.57}$$ where

W = Industrial, kW/t

W_z = Grindability index, kWl/t

R_{90} = Residue on the 90 micron sieve

Figure 6 shows a graphical representation of the transfer factor W/W_z:

$$W/W_z = 6.38\ R_{90}^{-0.165}\ W_z^{-0.43}$$

3.0 COMMINUTION (cont'd)

3.5.1.3 Zeisel's method [32] (cont'd)

When actual means for testing according to Bond's and Hardgrove's methods are not available, the MOHS scale is used in the field to give a rough idea about grindability through the hardness of the material. This method is based on the ability of a material to abrade. It is divided into a scale of ten standard minerals which are listed below in increasing order of hardness:

- Talc
- Gypsum
- Calcite
- Fluorite
- Apatite
- Orthoclose
- Quartz
- Topaz
- Corundum
- Diamond

3.5.1.4 Crushability

Although a crushability test should not be understood in the same way as grindability tests, there are some crushing resistance measurements which are frequently used by crusher suppliers, in order to select the proper comminution machine.

For a given rock or mineral sample, laboratory tests can prove or disapprove the relative merits of various types of crushers. The normal procedure is to test crush a representative sample of the

3.5.1.4 Crushability (Cont'd)

material and then determine the product size gradation. By comparing screen analysis and other criteria with those associated with familiar materials, an overall crushing performance as well as power requirements can be estimated.

While there is no direct measurement of "resistance to crushing", it is possible to measure comparitive strength and the elastic properties of a material.

Abrasiveness should also be estimated, though it is difficult to predict the abrasive action of rocks and minerals. Abrasiveness can be determined either from prior experience or by tests in semi-industrial plants. Pennsylvania Crusher Corporation (23) proposes the following method: A sample is rotated for 15 minutes in a drum with a steel paddle. After having measured the average milligrams of weight loss by the paddle, a relative index of abrasive action is determined. Some relevant data are given below:

Very abrasive: Barite, basalt, bauxite, cement clinker, clay, granite, gravel, quartz, sand slag
Mildly abrasive: Bentonite, cement rock, charcoal, coke, diatomaceous earth fluorspar, gypsum, limestone, marble, shale, phosphate, dolomite
Low abrasive: Coal, cryolite, lime, potash, talc

Table 3 shows some abrasive indices.

3.5.2 Size distribution measurement of crushed and ground products

An irregular shaped particle has no unique dimension and its size is usually expressed in terms of the diameter of a sphere that is equivalent to the particle. In theory, several definitions of

3.5.2 Size distribution measurement of crushed and ground products

particle size based on equivalent sphere have been proposed as reported by Lynch[18]. Some examples of these are:

- Surface diameter is the diameter of a sphere having the same surface area
- Volume diameter is the diameter of a sphere having the same volume
- Stoke's diameter is the free-falling diameter in a laminar flow region
- Sieve diameter is the width of the minimum square aperture through which the particle will pass.

For irregular particles, the measured size usually depends on the method of measurement. For example, sedimentation and elutriation analyses are expressed in terms of Stoke's diameter. Sieves provide the sieve diameter.

If microscope method is kept apart because not very frequently used for the routine plant production, two types of analyses summarize the present procedures in laboratories:

•Coarse Product:

The sieve analysis is the commonly used method. The sieve series complies with the ASTM standards. Though the bottom sieve corresponds to an aperture of 26 microns, it turns out very difficult to rely on the results of a sieving below 70-50 microns, the reason being that even suitable particles cannot pass through the sieve on dry. In industries where the finished product is very fine such as cement, the 325 MESH (45 microns) analysis, for example is done on wet sieving.

3.0 COMMINUTION (cont'd)

3.5.2 Size distribution measurement of crushed and ground products (cont'd)

•Flour:

When the product is very fine, the fineness may be expressed as a specific surface, surface/volume (or weight) or by its complete particle size distribution. The laboratory apparatus which are of common use today are:

- Specific surface measurement: Two apparatus are generally used i.e. the Wagner turbidimeter and the Blaine permeability apparatus. The first one is a sedimentation apparatus and uses Kerosene as dispersing agent. Its main advantage is that it can also identify the distribution of the different sizes of the particles. The Blaine apparatus is based on the permeability principle and is used to determine the specific surface of a given material.

The same material analysed by both methods will be given two different values of its specific surface, as illustrated by the ASTM Standard Specification which requires minimum specific surface for cement of 160m^2/kg by the turbidity test and 280 m^2/kg by the air permeability test, on the same cement grade.

In fact, a "true" value for the powder specific surface is still unknown. However, when a specific surface is mentioned, it is usually understood that it is the Blaine.

-Size distribution measurement: Excellent apparatus are available on the market. Some are based on the sedimentation principle where the concentration of particles are determined by means of a beam of x rays. Others use the light scattering of a laser beam by particles in suspension in a liquid. The results may be presented either as a continuous particle size distribution curve or as cut sizes. In practice, these apparatus differ by the sample

preparations and principally by the particle size fractions they can handle. In general, they are accurate and can identify one micron particle, the largest size being about 150 microns. Here again, the results from a particle size analyzer to another do not coincide exactly but are closer to each other than in the case of Blaine and Wagner methods for the specific area determination.

4.0 CRUSHING AND GRINDING MACHINERY

4.0 CRUSHING & GRINDING MACHINERY

4.1 Crushing Machinery

Basically, the four types of crushers used in industrial size reduction processes obey preferentially and respectively one of the principles described in a previous section. The series of jaw, cone and gyratory crushers applies principally to the compression work. The impactors, as their name implies, work by impact, the roll crushers by shear action, whereas the hammer mills work by attrition.

- Jaw Crushers (see Figure 8)

For crushing of hard, abrasive materials, jaw crushers are often preferred, since this type of machine will crush virtually any mineral. Jaw crushers differ substantially from other types of crushers. There is no rotary motion in the crushing cycle and all crushing is done by compression of the feed material between two massive jaws.

The moving jaw is balanced so that only a small percentage of the power is needed to move the jaw itself. In general, behind the stationary jaw are shims, used to compensate for plate wear and to adjust the closed side setting. Product size is determined by the distance between the lower end of the jaws.

Crushing surface of jaw plates is made of a variety of forms: smooth plates (fine crushing - brittle rock), ribbed plated (coarse work, glass). Size of feed that can be taken depends mainly upon the gape, the thinkness of the larger block should not exceed 80-90% of the gape in order to avoid frequent mouth clogging. Certain manufacturers propose equipment which can take feed sizes up to 46". On the other hand, reduction ratio are low, 3 to 8, in most cases. The material in jaw crusher can be fragmented down to approximately 1".

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.1 Crushing Machinery (cont'd)

The installed specific power consumption is low, about 0.3 kWh/t HERSAM's[30] formula gives the hourly production:

$$Q = 30 \frac{T^2 + 2ST}{G-S} .n.W.D.K.d$$

Where G and S are the inlet and outlet openings when the jaw is in closed position, T is the difference of opening at the outlet, n corresponds to the parameter RPM, W is the width of the jaws, D is the vertical height of the crushing chamber, d is the apparent density of the crushed product and K is a constant which depends on the sample "crushability", the shape and surface of the plates. In general, K = 0.75.

Size of product varies somewhat according to the characteristics of feed and to its sizing. The size distribution in a jaw crusher is shown in Figure 13-1).

- Gyratory and Cone Crushers (See Figures 9 and 10)

The gyratory crusher consists essentially of a fixed crushing surface of an inverted cone around the axis of which gyrates a movable crushing surface. It may be looked upon as a jaw crusher wound around a vertical axis. Adjustments of gyrator crushers includes the width of discharge opening, throw and speed. Reduction ratio ranges from approximately 4 - 12 (mostly 5-8). The size of feed is governed by the same considerations as apply to jaw crushers. The HERSAM capacity formula is supposed to be applicable to gyratory crushers as well as jaw crushers, but even with a readjusted K (0.4 instead of 0.75) deviations with actual field results are important. Size of product is closer to that of jaw crusher (see Figure 13-2).

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.1 Crushing Machinery (cont'd)

The cone type crusher differs from the gyratory as modified for fine reduction. It has a longer crushing chamber. A typical product size is shown in Figure 13-3.

Figure 14 gives the limits of utilization, of jaw and gyratory crushers [2].

- Single Roll Crusher (see Figure 7)

The single roll crusher has a roll assembly consisting of a roll shaft and a fabricated roll shell with generally integral fixed teeth. In the single roll crusher, three different methods of reduction occur: impact, shear, compression. Entering the crusher through the feed hopper, the feed material is struck by the teeth of the revolving roll. While some breakage occurs here by impact, the rotation of the roll carries the material into the crushing chamber formed between the breaker plate and the roll itself. As the turning roll compresses the material against the stationary breaker plate, the teeth on the roll shear the material. The discharge end of the crusher is completely open. There are no screen bars and consequently, there is no recrushing of the sized material, a factor that helps to reduce power demand while minimizing product fines. The clearance which then determines the product size is adjustable from outside by a shim arrangement. Applications include coal, aggregate, limestone, chemicals, phosphate rock, shale i.e. non-abrasive and medium hard material. Single roll crushers are superior to either jaw or gyratory crushers for wet or slippery materials. Such machines have capacity ranging from 50 to 2000 t/h.

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.1 Crushing Machinery (cont'd)

The power consumption depends greatly on the nature of the feed rock: 0.15 kWh/t for a good limestone and 0.3 kWh/t for gypsum. Reduction ratio is in general 3 to 4 but may reach 6 in case of soft feed. Figure 13-4 gives an indication of the size of the product.

- Hammer Mills (Figure 11)

Hammer mills are among the oldest yet still the most widely used crusher designs. Although recent years have witnessed the introduction of new types of crushers, many are a refinement of the basic hammer mill design to serve more specialized purposes. Its use as a rock crusher is confined to the easily crushable materials such as phosphates, gypsum, barite, cement rock and medium hard limestone.

Hammer mills are used either as one-step primary crusher for reducing run-of-quarry material to as small as 1" size or as secondary crusher taking 4-8" primary crusher product down to 3/4".

In-product is first reduced by dynamic impact; crushing then occurs by attrition and shear in the second zone, when slight clearances exist between hammers and screen bars. This second zone is the final sizing zone for the product. One of the advantages of hammer mills is their ability to produce the specified top size without the need of a closed-circuit system. Hammer mills, in general, produce fines, since large particles cannot escape the cage bars until sized, resulting in a minimum of oversize and a product uniformity. Cages can be adjusted to regulate product top size.

Some hammer mills are symetrically designed crushers with a rotor that can be run clockwise or counter-clockwise.

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.1 Crushing Machinery (cont'd)

Hammer mills can handle up to 800 t/h depending on the nature of the feed. The specific power consumption is high in cement raw materials 1.5 to 2.0 kWh/t - since the reduction ratio is the highest of crushing machines.

Hammer mills are very sensitive to moisture, the critical range is about 10%. In case of moist and plastic feeds, capacity may drop by 30 to 50%. For this purpose, non-clog hammermills are used. As regards abrasiveness wear, the silica content of the material should not exceed 5-6%.

- Impactors (Figure 12)

Reversible impactors are used for secondary and eventually tertiary crushing, and occasionally for primary crushing. They are used for reduction of ceramics, lime and agricultural limestone, cement raw mix, gypsum, fertiliser, chemicals and other materials.

Impactors are recommended when certain requirements exist: high reduction ratio (35 to 1); high capacity; cubically shaped well graded product; minimum fines. These crushers can be easily adjusted to produce a wide variety of product sizes. When a maximum of fines are desired, the units are merely operated at a higher speed. When fines must be kept at a minimum, the units are run at lower speeds.

Material drops through the centrally located feed chute directly into the rotor where it is struck by the rotating hammers. The material then impacts against the breaker blocks and rebounds into the path of the hammers. There are no cage bars or screens, therefore there is a minimum of attrition crushing. The bottom of the crusher is entirely open and the sized material passes out freely.

4.1 Crushing Machinery (cont'd)

When the product must be held to a specific top size, the machine should be operated in a closed-circuit system.

Some impactors are available in capacity exceeding 2000 t/h.

One of the big advantages is that they can be erected in mobile installation because of their relative small size. As far as the stationary installations are concerned, the relative small size and weight require smaller foundation and supporting structure, compared to other types of crushers. In general, overall capital cost of impactor installations as well as their operation cost are much lower than other types of crushers. Nowadays, only special specifications of finished crushed products justify the selection of other types of crushers for size reduction of solid rocks.

There are other crushers which are used in very specialized industries. All of them use the same crushing principles. They do not deserve a special description but are listed here after for the reader's interest:

- Granulators, for moderately hard materials
- Twin rotor impactors, for wet sticky materials. The crushing chamber walls may be heated by a circulation of hot gases.
- Non-clog hammer mills, with a travelling breaker plate
- Spring rolls, rarely used nowadays
- Stamps, not used anymore
- Breakers, especially for run-of-mine coal crushing and conditioning (cleaning).

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.2 Grinding Machinery

Tumbling mills are the most often encountered in the processing of industrial minerals .

Grinding takes place in a grinding drum (cyclindrical or conical) that rotates around a horizontal axis and is internally lined against wear. The drum is filled with free grinding bodies that are normally made of wear resistant material. During rotation, the grinding bodies are set in motion and tear, crush or break apart the material that is fed into the mill for comminution.

Two principles of comminution summarize the process by which particles are size reduced: cataracting or cascading.

At higher speeds, the grinding media will be thrown out into space within the upper region of the mill (cataracting). In this way, the grinding process is characterized more by impact fractures. At lower speeds, the grinding bodies are lifted up along the inner periphery of the mill and roll back down (cascading). This circulating movement of the grinding bodies creates the attrition tearing and crushing grinding of the material between them.

Thus, the speed of rotation determines the grinding work in a tumbling mill. The actual mill speed is generally expressed in percentage of of the critical speed and varies between 65 to 90, the most common figures being 70-75%. The critical speed is that speed of rotation at which the centrifugal power neutralizes the force of gravity which influences the grinding media. Provided that there is no sliding action, grinding bodies are held to the liner of the grinding chambers without dropping and therefore do not perform grinding work. The critical speed, in revolutions per minute is:

4.2 Grinding Machinery (cont'd)

$N = 42.3/\sqrt{D}$ if the internal diameter of the mill is in meters

or $N = 76.6/\sqrt{D}$ if the internal diameter of the mill is in feet.

The shape that has withstood the test of time are cylindrical and cylindro-conical. The ratio of diameter to length ranges from 0.2 to 0.3 in wet process, but may be higher than 4 in dry process and multicompartment mills. The inner surface ranges from smooth to various degrees and forms of roughness. In wet, the relative diameters of inlet and outlet openings, taken with mill lengths, determine the mean slopes on which pulp flows, ranging from a small fraction of an inch to several inches per foot.

The diameter of the mill affects impact magnitude in cataracting. The length of the mill will then follow in respect to the required ratio. In general, rod mills are made long in proportion to diameter in order to prevent the rods from becoming crossed. In wet process, ball mills,taking coarse feeds currently 3/4" - 1",are made of large diameter to insure heavy impacts and lengths are kept down in order to obtain the steep pulp gradient necessary with coarse material to minimize the retention time. With finer feeds, it is possible to maintain rapid flow with a lower pulp gradient. Still in wet process, ball-tube and pebble tube mills are made long to gain time-factor while keeping down diameter to save power and liner wear. In dry process, the ratio L/D, the most frequently used in ball two compartment mills averages 3, the main concern being the value of the circulating load required in closed circuit. In open circuit, the mill length can be higher for the benefit of a longer material retention time, since the final fineness should be reached in one pass. Compound mills comprise more than one compartment; the first compartment is devoted to the coarse grinding whereas the following compartment(s) is reserved to the fine grinding. When necessary, the first compartment is a dryer.

4.2 Grinding Machinery (cont'd)

The capacity of grinding in tumbling mills is related to the useful volume. In wet grinding, Taggart[30] defines as effective volume that between the shell and a plane included in the direction of the mill axis and extending from the bottom of the mill inlet to the bottom of the outlet annulus, diminished by the volume of tumbling media within this zone when the mill is at rest. The maximum rate at which pulp can be flowed through the mill depends upon the pulp consistency and the difference in elevation between inlet and outlet lips.

In dry process, the major parameter to be controlled is the volume load i.e. the volume of grinding media charge after having purged the mill, in proportion to the volume of the grinding chamber. The volume load varies between 28 and 40% (a figure frequently used in cement manufacturing is 32% in Europe and 38% in North America). Although many formulas have been proposed, the main objective of every miller is to use fully the installed power. In fact, the mill throughput does not have very much effect in the power consumption. The interior surface of mills is protected from wear and corrosion by rubber, metallic or a combination of rubber and metallic wear resistant liners.

Liners also control the lifting effect on grinding bodies. In wet grinding, shell liners usually differ in type according to whether the mill feed is coarse or fine. Liners for coarse feed produce sensible ridges parallel to the mill shell while those for fine feeds are smooth or uniformly roughened. Height, spacing and conformation of ribs determine the mechanical action of the mill shell on the tumbling charge (magnitude of the cataracting action).

4.2 Grinding Machinery (cont'd)

Basically, the same types of liners of wet grinding are used in dry process. The most common are: wave liners, double wave liners and lifting liners. However, a new profile of liners namely classifying liners is being widely used in finished grinding today. In general, classifying liners are installed in the second compartment of compound mills and classify balls in decreasing size order in such a way that ball sizes are continuously adapted to the material to be ground all along the grinding compartment.

4.2.1 Grinding Media

The grinding load is the working part of the mill. It draws substantially the same amount of power whether it does any useful work or not. The amount of useful work that it does differ with the shape of the tumbling bodies, their size, their quantity and the kind of material they are made of. Cylindrical rods, spherical balls, and to a lesser extent, rounded pebbles are the media used in substantially all mills today.

Rods occupy the greatest percentage of struck volume. They permit a shorter throughput residence time. Taggart [30] mentioned that rods are superior to balls for feeds in the range from of 1/2" to 1" when the mill is not called upon to produce a very fine output.

Balls are superior at coarser feed size or for finer grinding, because the mill can break cataracting the large lumps by hammering. Balls have greater surface per unit weight and have to be proved more efficient than any other grinding medium shape.

Size of media most suitable for a given tumbling mill is a given service is still, today, far from being established.

4.2.1 Grinding Media (cont'd)

However, certain facts may be summarized as follows:

- In an operating mill, a seasoned charge normally produces better grinding than a new charge, particularly in wet process. That may be interpreted as a "natural" grinding media gradation.
- A coarse feed requires larger media than a finer feed.
- The smaller the particle, the smaller the optimum diameter of medium.
- The harder the ore, the larger the ball needed.

Rod mills normally carry from a 35 to 40% by mill volume rod charge. The generally recommended relationship of rod length to mill diameter is 1.4 to 1.6. Below 1.25, the undesired risk of tangling increases rapidly. For the largest diameter rod calculation and the grinding charge distribution, Rowland and Kjos [25] propose:

$$R = 25.4 \frac{F^{0.75}}{160} \left[\frac{W_i S_g}{(\% C_s)(3.281D)^{as}} \right]^{0.5}$$ in case of rod mills

R = Diameter of largest rod, in mm
F = Feed size 80% passes, in microns
W_i = Bond's work index
S_g = Specific gravity
C_s = Critical speed
D = Diameter of inside shell liners, in meters

4.2.1 Grinding Media (cont'd)

Grind rod charges in start-up equilibria - percent weight

Rod Ø, mm	125	115	100	90	75	65
125	18					
115	22	20				
100	10	23	20			
90	14	20	27	20		
75	11	15	21	33	31	
65	7	10	15	21	39	34
50	9	12	17	26	30	66

In case of ball mills, the ball load should be as follows:

$$B = 25.4 \left(\frac{F}{K}\right)^{0.5} \left(\frac{W_i \, S_g}{(\%C_s)\ (3.821D)\ 0.5}\right)^{1/3}$$ = diameter of largest ball in mm

Except for K which is given below all other terms the same as for rod case.

Wet overflow open circuit or closed circuit	K = 350
Wet diaphragm open circuit or closed circuit	K = 330
Dry - all cases	K = 335

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.2.1 Grinding Media (cont'd)

Ball Load Gradation - Percent Weight

Ball Ø, mm	115	100	90	75	65	50	40
115	23						
100	31	23					
90	18	34	24				
75	15	21	38	31			
65	7	12	20.5	39	34		
50	3.8	6.5	11.5	19	43	40	
40	1.7	2.5	4.5	8	17	45	51
25	0.5	1.0	1.5	3	6	15	49

The above formulae and data may greatly differ from actual practices.

Particularly in a closed circuit dry grinding, if a minimum of fines is required in the final product, the mill operates at a high circulating load. This will lead to a more porous load with two or three large ball sizes in each compartment.

4.2.2. Mill Types

These can be classified in two groups, wet grinding mills and dry grinding mills, according to their main usage. However, some of the ball mills are used in wet process as well as in dry processes.

- Wet grinding mills

- Rod mills (Figures 15 and 18)

The rod mill has a cylindrical shell with an L/D ratio of 1.3 to 3.0. It is made mainly in overflow and open end types which differ by the mill discharge design.

4.2.2 Mill Types (cont'd)

Rowland and Kjos[25] propose the following equation to determine the power required.

$$kW_r = 1.752\ D^{1/3}\ (6.3 - 5.4\ V_p)\ \%C_s$$

Where

kW_r = kilowatts per metric tonne of rods
D = mill diameter inside liners, meters
V_p = fraction of mill volume loaded with rods
$\%C_s$ = fraction of critical speed.

In rod mills, feed is usually 1/4 to 1" maximum. Pulp density varies from 75% solids for coarse feeds to 60% in fine intermediate grinding.

- Overflow Ball Mills (Figures 16-1 and 19)

Overflow mill is essentially like the rod mill except that in general the ratio of length to diameter does not exceed 1.5. Diameters in ordinary use are 5 to 10 feet.

Pulp density ranges from 50 to 85% solids.

- Conical Ball Mills (Figure 17)

The true conical mill is characterized by a shell having a short cylindrical section and a conical discharge section. The L/D ratio in the cylindrical section is, in average, 1/3. The main feature of conical mills is that larger balls tend to segregate in the cylindrical section and coarse material tends to be held or returned there until it is broken. Discharge restrictions are necessary when conical mills are operated with high ball charges. Grates are usually used.

4.2.2 Mill Types (cont'd)

Volume load ranges from 35 to 50%. Size of feed averages approximately 1 in.

The specific power consumption increases with the size of the mill.

- Cylindrical Grate Ball Mills - Tube Mills (Figure 16-2)

Grate ball mill is a cylindrical mill with the same general dimensions as the overflow ball mill, but furnished with a grate near the discharge end of the shell. Some sort of elevator is provided between the grate into the discharge trunnion. Reduction ratio ranges from 1.2 to 140 with a mean of 25. The mean ratios correspond to reduction of 1/2 to 1/4" feeds. When the length to diameter ratio is higher than 2, ball (and/or pebble) mills are usually termed tube mills. They are used for fine grinding. This end is accomplished by increasing length. Tube mills give a finished product passing at 50-60 microns. Pulp density is usually from 60 to 70% of solids with pebble charges and 70 to 75% with ball loads.

- Closed Circuit Operation

In closed circuit operation, the practice of discharging partly finished pulp from a mill, removing the finished portion and returning the balance has become an essential part of fine size reduction. Both screens and sedimentation-type sandslime separators have been used to remove the fines. Mechanical classifiers predominate overwhelmingly.

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.2.2 Mill Types (cont'd)

- Dry Grinding Mills

- Autogeneous Mills (Figure 20)

They belong to impact machines category. Autogeneous grinding is that in which the feed is itself the grinding medium. The "Aeorofall" mill is a crushing device which employs this principle, though for certain applications of steel balls are employed to empty a small portion of the feed. The Aerorofall mill is a short tube with a large diameter. The L/D ratio is approximately 5. It is equipped inside with lifters which carry the charge upwards as high as possible in order to give the material a height enough to assure bursting of particles when they drop.

In addition to this impact action, material in the toe of the mill is also pounded by the lifters on their return to the bottom and material being lifted again is ground by attrition before it is released to fall and break by impact again.

The reduction ratio is high. For design purposes, the mill feed size is related to the mill diameter as per the equation of MacPherson and Turner.

$$d = 0.95\, D^{2/3}$$

where d = size that 80% of the rock passes in.

D = mill diameter inside shell, feet.

Discharge of the mill is achieved by action of a gas stream velocity which controls the particle size of the mill product. The gas loaded with ground particles leaves the mill to pass into succeeding cyclones or separators. Depending on the finished product required,

the oversize particles are returned to the same mill or go to another circuit.

In autogeneous mills, the possibility of using hot gases is widely used when the feed moisture content exceeds 2%.

Because of the method of particles transportation, 50% of the power consumption is taken up by the pneumatic system. DUDA [5] estimates the air requirement of 2 - 3 m^3/kg of mill feed. The total specific power consumption is approximately 20 Kwh of product.

A typical product size distribution is given in Figure 22-1.

-Roller Mills (Figure 21)

As a result of the development of high wear resistant steels, fast running mills are becoming increasingly popular. Roller mills have a lower specific energy consumption than tumbling mills. They work as air swept grinding mills.

With built-in air separators, these mills operate frequently as drying-grinding mills in closed circuit.

The roller mills work the principle of two to four grinding rollers riding on a horizontal grinding table or grinding bowl. The shape of the rollers and their disposition vis-a-vis the grinding table differ from one supplier to another. A feature that most types of roller mills have in common is the hydropneumatic suspension of the grinding rollers, exerting a pressure which can quickly be altered while the machine is running. Such adjustments may be necessitated by, for example, a change to a different type

4.2.2 Mill Types (cont'd)

of feed. The feed usually enters the mill to fall on the centre of the revolving table. Centrifugal forces then causes it to move outward through the annular grinding zone where it is trapped under rolling elements. To elutriate fines from the grinding zone, an uprising stream lifts the material to the classifier located usually at the top of the mill casing where the coarse particles are separated from the fines. The coarse particles drop back into the grinding zone whereas the fines together with the mill air leave the whole system. The air may be heated for the purpose of drying the material. The moisture of the feed material can amount up to 15 - 18%.

The fineness of the final product can be adjusted by varying the speed of the separator and may range from 94 to 70% passing 170 mesh (88 microns).

The specific power consumption depends on the feed moisture content and the degree of fineness of the grind. To grind coal upto 92% passing 170 mesh, the power consumption as reported by DUDA [5] is approximately 13.5 kWh/t.

-Tumbling compound Mills

These mills include many variations of the rotary equipment described in wet process grinding with special adaptations for drying as part of the mill or incorporated in the overall circuit.

Diaphragm Discharge Ball Mill - Single or Multicompartment

The diaphragm discharge ball mill can be used for wet and dry process.

4.2.2 Mill Types (cont'd)

When used for dry grinding, the unit can be fitted with a drying compartment to provide a greater degree of drying in the mill. In this particular type of dry-grinding installation, the amount of air drawn through the mill is kept low because the material is discharged from the mill by mechanical means. This is advantageous for the grinding process which will not be disturbed by the air velocity, but is a disadvantage for the drying of the raw material.

In general, the feed should not exceed approximately 5/8" in size and 8% in moisture content, this is subject, of course, to the grindability of the rock.

A typical product size distribution for a ball mill is given in Figure 22-2.

-Airswept Mill

In the airswept mill, the raw material enters with the air through the feed trunnion. If a drying operation is needed, the material is predried in a drying chamber which is equipped with lifters that intensively distribute the material over the entire mill cross section. The dryer might be internal to the large feed end bearing - as the first compartment of a two compartment mill - or external like an overside drum feeder.

The dried material is transported to the grinding chamber through a lifting diaphragm. The stream of air drawn through the mill removes the fine particles. This fine material is then fed to a classifier where any oversize material is returned to the mill. Airswept mills have low power consumption (mill only) but must be evaluated with fan power to compare the total kWh/t consumption. This normally exceeds conventional mill power.

4.2.2 Mill Types (cont'd)

The feed, in general, does not exceed approximately 1 1/4" in size and 15% in moisture content.

-Double Rotator Ball Mill (Figure 23)
The double rotator mill incorporates the advantages of both the airswept mill and the diaphragm discharge mill.

In the first compartment, material is "flash dried" by high volume of airswept gases. It is then conveyed into the second compartment for coarse grinding and exits through the periphery of the mill shell. The material is then mechanically transported to the air separator. The oversize is fed back through the other end of the mill (third compartment) for fine grinding.

The discharge of the mill is large enough to handle high volume of vent gases with relatively high grain loading and material product of both compartments.

This type of mill handle feed with moistures upto 15% and sizes upto 2".

4.2.3 Classification in Dry Grinding Circuit

When fine grinding is performed in closed circuit, the mill discharge is conveyed to a sizing device where the suitable material is trapped and separated from the coarse part or tailings. These tailings will then return to the grinding system. There are basically two types of devices which make a separation work: cyclone and separator. Dust collectors are not included because the primary objective is different than of separators. A brief outline of the separation machinery is given below:

4.0 CRUSHING & GRINDING MACHINERY (cont'd)

4.2.3 Mill Types (cont'd)

-Cyclones or Centrifugal Collectors - Static classification -
It accomplishes removal of solid particles. Gas loaded with particles enters tangentially near the top and is forced down in a decreasing spiral to the particle outlet trap. Particles are precipitated to the periphery and slide down while clean gas forms a vortex in the center and travels upward into the clean air outlet.

The first objective of cyclones is to work as dust collector, where they do not particularly excel. Because of a rather low efficiency, cyclones can be used as classificator. Exhaust air loaded with fine particles is then sent to a conventional dust collector for the air-particle separation.

-Separators
Pneumatic air separators are the heart of a closed circuit. Many types of grinding separators are presently on the market. The mechanism of separation may be summarized as follows:

The material is fed onto a rotating distributing plate. Centrifugal force propels the particles into an air current produced by a fan and hence coarse separation takes place immediately. A system of rejector blades modulates the passage of the particle laden air stream permitting the selection of particles of certain dimensions. The particles which have been entrained pass through as finished product and the remainder is returned for regrinding.

-Circulating Load and Separator Efficiency
The material returned to the mill by the separator is called Rejects, Tailings or Coarse. If R is the amount of tailings coming from the separator for further grinding, and F, the new feed entering the system, then the circulating load is: $CL = R/F$.

4.2.3 Mill Types (cont'd)

The circulating load can reach very high values (up to 2000%) depending on the grinding logics used by the mill. The circulating load is a function of the characteristics of the system feed, the mill type used and particularly of the finished product fineness distribution required. The classification-separation acuity of the separator is of the most importance, in order to fully use the benefit of closed circuit grinding which results in the lowest amount of overground (useless) particles. That is the necessary condition to obtain low specific power consumption.

4.2.4 New Developments

In addition to the roller mill presented in a previous section which is gaining more and more attention in comminution process, new types of mills are being placed on the market place.

-Planetary Ball Mill (Figure 25-1)

All other things being equal, the efficiency of a ball mill is proportional to the specific gravity of the grinding media. Tungsten carbide balls, for example, with a specific gravity of 14, are much more efficient than conventional steel balls at a specific gravity of 7.8; however, such grinding media is expensive.

The fundamental idea of the centrifugal or planetary ball mill is to replace the higher specific gravity of the grinding media by centrifugal force.

A planetcry mill consists of two or more parallel grinding tubes performing a gyroscopic movement around a common axis of rotation.

4.2.4 New Developments (cont'd)

Duda [5] reports that"Proceeding from the effective throughput of this planetary mill, it can be shown that the planetary mill demands only about 3% of the grinding energy a regular tube mill would require for the same fineness and output." Although the planetary mill is not a new idea, much development work is being presently performed in many countries to make this mill commercially feasible.

-Slant Mill (Figure 25-2)

Vivian [31] estimates that only 5% at most of the total balls in a given mill are actively grinding. The remaining 95% consist principally in a close-packed immobile ball bed. He also estimates that the actual time of grinding from impact until reforming the packed ball bed is extremely short, 0.1 second or some 2-3% of the mill rotation time.

Increased grinding rates could be achieved by activating and keeping continuously mobile a large proportion of the media.

The slant mill consists of an inclined cylinder which rotates around a central, horizontal axis. Rotation causes the ball loading and feed particles to roll from one end of the mill to the other end, since the ball mass is not confined between two ends, it shows no tendency to lift. At all speeds, the power required to operate the slant mill is almost independent of the amount of ball and feed loading. The measured rate of grinding in the slant is rapid because the balls are continually rolling and mixing with feed particles. The mill is essentially a fine grinding mill and consequently, the input feed must be relatively fine. According to the data provided by Vivian [31] on small mills, the specific power consumption drawn by a slant mill represents,in some cases,less than half of that drawn by a standard ball mill.

4.2.4 New Developments (cont'd)

-Vibrating Mill[4]

Very little has been published on this type of mill. The grinding circuit consists of two tubes working either in parallel or in cascade. The mean advantage is to be a narrow particle size distribution curve on the finished product.

Other methods are being investigated[28]. They are unconventional and do not yet have a fully established commercial market. The most promising of these are:

-Explosive disintegration technique involving impregnation and expansion stages.
-Thermal methods which consist in a sudden expansion of contained fluid.
-Electrothermal methods where local currents induced in the rock mass give rise to temperature gradients and spalling effects.
-Shock waves by electrical discharge.
-Ultrasonics - if a piece of solid would be made to vibrate at its fundamental frequency, this could be a very effective means of shattering.

5.0 OPTIMIZATION

5.0 OPTIMIZATION

The means which might be used to optimize the wide range of comminution operation are not easily amenable to classification. The main stages of size reduction, blasting, crushing, grinding may be approached in the same way. In all cases, the size reduction of a given material is governed by the initial form of the rock, the profile of the finished product and the equipment in which the fragmentation operation is to be achieved. That is for what might be called, the static point of view. Indeed, there is a dynamic point of view. The dynamic point of view deals with the operations of comminution where optimization bases on the utilization factors of the installation, the maintenance program and the logics of process control.

5.1 Blasting-Crushing

Because the crushing operation begins at the mine or quarry level, a short description of the blasting operation is necessary. The purpose of blasting is to reduce rock to a size at which it may be economically handled by crushing machinery. The maximum size of the products of blastings must be small enough to enter the feed ports of the crushing machines employed. The blasting process must produce rocks of size between 1 and 2 meters. A typical size distribution of the products of blasting is given in Figure 32. (28). After a primary blasting, some large boulders may need a secondary blasting. It is generally estimated that 95% of explosive goes into primary and 5% into secondary blasting.

The economics of blasting as related to the downstream operation of crushing varies considerably from quarry to quarry. In general, for smaller outputs, blasting costs will be higher per tonne of rock than for larger outputs. This is partly because, the crushing machinery will be less massive and the degree of blasting would be greater.

5.0 OPTIMIZATION (cont'd)

5.1 Blasting-Crushing (cont'd)

Hence, optimization will consist of producing the largest blocks possible which may enter the crusher inlet opening.

5.1.1 Crushing machines selection (see Table 4) [21, 28].

In the proper selection of a machine, a number of factors should be taken into consideration. Some of the most important factors are as follows:

- Feed Characteristics: Moisture, hardness, abrasiveness
- Product Requirements: Top size particle, size distribution and shape of particles, content of fines.
  These two specifications by themselves permit a first and decisive selection.
- Final Reduction Ratio: After the above two requirements have been met, the selection of the crusher should be made which gives the highest reduction ratio, in order to avoid multistage crushing. This procedure is particularly effective when the final objective is to obtain a product as fine as possible, provided that a fine comminution - milling will follow. Further, the desired reduction ratio will dictate the selection of the crushing vis-a-vis open or closed circuit.
- Capacity and Power Consumption: These two parameters are closely related. The large crushing plants require lower energy consumption. This is due to the fact that large crushers allow large particle size at the inlet, thereby permitting less blasting. This results from feed characteristics and partly from the product requirement factor affecting the specific power consumption of a facility of higher reduction ratio for same crushed product size.

5.0 OPTIMIZATION (cont'd)

5.1 Blasting-Crushing (cont'd)

Furthermore, based on the theoretical calculation, it appears that the specific power consumption, kWh/t, does not increase with the size of the crusher. In the worst cases, the kWh/t remains constant, whereas in most conventional machines - jaw, gyratory and roll crushers - the specific power reduces with increased size. [28]. Unlike grindability tests, crushability tests cannot predict the industrial power consumption. The mobility of the installation and the capital investment are other considerations effecting the solution of the crushing equipment. Thus the kWh/t factor is an incidental result based on the selection of the machine. The optimization of a crushing installation will depend on specific requirement of the problem and must be taken into consideration at the design level. As stated above, the major component of optimization is the proper selection of the type of crusher. In case where the crushing unit already exists the operation has to be investigated to optimize the crushing requirements.

5.1.2 Crushing Operation [21, 28]

In order to achieve the degree of optimization, the following rules should be adhered to:

- Feed homogeneity and continuity

Any change in the feed characteristics will be followed by a drop of the crushing unit performance. Moisture must be considered as the most important paremeter, particularly for those machines which are very sensitive to wet materials such as gyratory and hammermill types. Large variations of moisture content induce a severe drop in the production rate and may change the crushed product size along with size distribution. The hardness and abrasiveness usually do not

5.0 OPTIMIZATION (cont'd)

5.1.2 Crushing Operation [21, 28] (cont'd)

change drastically for a material proceeding from the same quarry. In general, slight variations of mechanical properties of the feed material be smoothened by the adjustment of the crusher settings. Great attention should be paid to the homogeneity of the size distribution of the feed material. Quarry development should be co-ordinated to the crushing operation. A change in the feed size and/or size distribution will inevitably lead to a different product size gradation from that of the plant objective. Regardless of the directions of the feed size changes, a drop of the overall performance of the crushing installation is to be expected, particularly when changes in feed size are too important and cannot be absorbed within the crusher settings range, even in an automated installation. The second aspect is the feed distribution. It is very desirable with all crushing machines that the feed be controlled. The main concern is to use the total capacity of the crushing unit. A crusher running half empty will not draw 50% of the installed power but much more. An underfed machine induces very poor efficiency both in terms of specific power consumption, and in terms of particle size distribution of the crushed product, too many (unwanted) fines for instance. A feed distribution system and regulation should be mounted at the entry of the crusher. Also, a chain curtain may be needed in order to equalize the feed at the inlet.

- Basic Rules in Crushing Operation

When intermediate products are needed (aggregate sector, for example), when imperative beneficiating operation are to be involved within the crushing operation (asbestos treatment for example), or when the feed characteristics are limitative, then a multistage crushing plant is required and some rules must be observed regarding the optimization

5.0 OPTIMIZATION (cont'd)

5.1 Blasting-Crushing (cont'd)

of the installation - kWh/t and finished product quality. These rules are:

- Even when a crusher has the capability of achieving a high reduction ratio, it is normally more efficient to operate the crusher at mid-setting rather than choosing the closest setting which offers the greatest reduction ratio. The main consideration on each stage for maximum production is efficient power draw.
- There is an optimum setting for each crusher and an optimum number of stages required for maximum plant production based on the individual characteristics of the material being crushed. Overloading the crusher does not increase production but instead is counterproductive and decreases the lives of the crusher components and damages the final product characteristics.
- The crusher should be fed so as to be operating at or near continuous full load horsepower capability. Efficient use of power through proper utilization of the crusher, with respect to feed and product requirements will determine the optimum specific power consumption, Kwh/t.
- The range of feed sizes and product sizes for each crushing stage overlaps into the succeeding and preceding stages.
- The top size of the feed material should not be more than approximately 90% of the crusher inlet. In case where more than 10-15% of desired crusher product is present in the feed, this must be scalped. Here again the upstream operations (blasting or preceeding crushing stage) must be co-ordinated, since each classification step adds to the operation unit costs. When the classification is not imperative under the process point of view, it should be avoided.

5.0 OPTIMIZATION (cont'd)

5.2 Grinding

Grinding operation is more complicated than crushing in many aspects. Grinding can be performed in dry process as well as in wet process, in a monocompartment as well as in a multicompartment mill. The choice between an open and a closed circuit is not only dictated by kWh/t but in many instances preferentially by the profile of the finished product. That brings up the problem of the separator acuity, the characteristics of which are little known for very fine grinding plant. In cement grinding for example, circulating loads are reaching very high values. A 1000% circulating rate is not very uncommon in industry. This compares to the 50 or 100% of circulating load encountered in crushing.

Moreover the magic grinding model applicable to all cases does not seem to have been discovered. Many variables are simultaneously involved in a complex installation, which in some cases includes a drying operation in addition to the conventional grinding, classification tandem.

5.2.1 Selecting Grinding Machinery

In most cases, mills are fed by a crushed product. Factors which influence the selection of the proper grinding equipment are dependent on crushing operation performances. The selection of the adequate mill will depend on the feed size as supplied by the upstream size reduction and of course upon the finished product fineness required. Similar to the crushers selection, the moisture of the feed is of great importance. If the water content is higher than a certain value (10 - 15% , depending on the mineralogy of the material) and if the following stages of raw material beneficiation allow it, a wet grinding is chosen. When the grinding is to be done on a dry process

and the feed moisture content may lower the comminution performances, then a drying operation is added to the circuit.

The reduction ratio is the most important parameter in the selection of a mill. When designing a grinding unit, two data are given: capacity of the installation and fineness of the finished product. These two data taken together permit to make a selection on the number of size reduction stages (if more than one) and on the type of circuit (open or closed).

On the power consumption, the conventional BOND's theory cannot apply and it does not seem possible to foresee the power rate when designing a new grinding unit, unless data of similar installation treating similar (if not identical) feed are available. Only, field trials in the start up period can lead to the determination of the actual power consumption.

5.2.2 Grinding Operation

A rotary grinding mill is basically a constant power machine. Whether it grinds a full capacity, half or no capacity, a mill will draw a "basic" kWh which would roughly correspond to its motor power installed.

Thus any improvement in the capacity and fineness of the ground product can be achieved with very little added cost. Some general rules must be followed.

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

- Constant power maintenance

  The grinding media load should be maintained at its optimum level. The optimum level is the level at which 100% of the installed power is drawn when mill is running on load. In North American practice, this corresponds to approximately 38% of filling rate of grinding media. When mill is operated at high circulating load (high material throughout) the actual power consumption may even vary between 100 and 110% without any damage in the equipment.

- Maintenance of mills operating condition

  Once the proper charge level decided, it should be maintained with periodic additions of grinding media. Additions should be of the top of size media only. In a compound mill, greatest attention should be paid to the critical first compartment, which handles large feed and which experiences greater media consumption than the second compartment.

  When liners are badly worn, the cataracting action decreases. The charge begins sliding action back down the liners. In general, lower consumption results from this sliding action.

  It is often said that a good mill efficiency relies on the ability of the material to easily migrate from the inlet to the outlet of the mill. That is particularly true in dry grinding compound mill where super fine particles must be avoided. Not only a properly designed gradation of the grinding bodies but also clean grate slotes are of the great importance. Grate slotes are often plugged up by small pieces of broken or worn out balls. Once a year, the grinding load must be dumped and sorted in order to remove all the too small media and readjust the ball design.

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

- Proper gradation of grinding media - Separator efficiency
  A number of designs are proposed by mill manufacturers.
  The number of media sizes to be used for each compartment has not been universally accepted. In fact these parameters depend upon the logics of the grinding operation.
  Some plants prefer to have a rather long retention time of the material in the mill in order to obtain high fineness at the mill discharge. They would therefore choose a compact media load with four to six media sizes per compartment. In other plants, two to three media size in each compartment would be most effective, because the material retention time is shortened with such a porous, coarse media load. The mill discharge will be globally coarser, only because of a smaller amount of too fine (unwanted) material. The proper size particles are in sufficient quantities to be classified and separated in the next process stage.

  That brings up the separator efficiency question. It is well known that an important fraction of sufficiently ground product is returned to the mill as tailings. In cement grinding up to 70% of the fine particles entering the separator, suitable to be classified as cement, are returned to the mill with the coarse particles for further re-grinding. Some of the energy available for grinding is needlessly consumed in making fine particles finer.

  In order to avoid these too fine particles and because of the low efficiency of the separators available on the market place, the following suggestions are proposed:

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

- The retention time of the material in the mill should be rather short. To help in determining the optimum retention time, one may use the ratio of grinding media tonnage to material load (instantaneous charge) contained in the mill. This ratio in practice is approximately 7. If higher than 7, the mill is underfed, if lower than 7, the mill is overloaded and the grinding efficiency drops. With the proper ratio, the mill will produce a narrow particle size distribution which will help the separator to achieve a better selection of particles. Indeed, the separator efficiency is directly related to the amount of feed but also to its fineness. More precisely, the separator efficiency decreases when the feed amount and fineness increase. Because very little can be done in sizing the separator, unless systematically overdesign it, a great attention should be paid to the separator feed (or mill discharge) fineness, which should contain the least amount of super fines particles.
- Mill Length - Grinding Aids

  From the above paragraph, it is understood that long tumbling mills, with in general an L/D ratio $\geq$ 3, will be more difficult to master as regards to the material retention time. A permeable grinding media load may be insufficient to lower the retention time. In that case, the solution is in the use of grinding aids. It is claimed that grinding aids use leads to a production increase of more than 10%.

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

Grinding aids action can be two fold:

They first act on the material flowability and on the agglomeration of fines. This action results on better properties of migration of ground particles. The material retention time will then be lowered. Fine particles leaving the mill as soon as they are produced will not undertake any useless supplementary grinding. The grinding will then concentrate on coarser particles (fresh feed) increasing this way the production rate to the benefit of specific power consumption.

Grinding aids also act on the grinding bodies and liners coating. They generally make it disappear. The cushion effect of coating is avoided which will lead to a better breaking action of the grinding media and liners.

On the other hand, grinding aids are costly and should be used only in case of high fineness production, say more than 300 m^2/kg as specific surface Blaine, and when the mills are long.

- Feed Size Uniformity - Mill Venting

Although the proper charge level and gradation may be established, if the mill is not fed and vented (for dry grinding mills) properly, it cannot produce at its optimum value.

Size control is important particularly for mills which handle feed larger than $\frac{1}{4}$". For example, if a ball mill is designed to handle a feed of 100% at $\frac{1}{4}$", a feed change to 100% at $\frac{1}{2}$" will result in a capacity loss of approximately 5 to 10%. Rod mills tolerate oversize feed much better than ball mills as long as the operation is not already critical. Constant, uniform flow of new feed is naturally essential. This is true for both capacity and chemical composition, the latter being particularly important when two or more materials are being processed and when the mill serves as a grinder and as a blender.

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

- Moisture control is also important. In wet mills, moisture variations will affect the ground with more water giving a coarser product. Optimum slurry density should be established after experimentation; and the density should be maintained by matching the water flow rate and the material flow adjustments with a proportional control. For dry mill, if moisture content of the feed exceeds approximately 0.5 - 1%, controls must be available to measure and adjust the heat requirements.
  In dry mills, an air flow is required to remove fine particles and some of the heat of grinding to minimize coating. Depending on the mill system, these fines will go either to a dust collector where all the material is recuperated and sent as finished product or to a classification-separation stage where the coarser part of the material is sent back to the grinding system. The proper settings are specific to each industry. However, an ½" suction pressure should be available at the mill feed spout to prevent dusting or backflushing.
- Closed Circuit Grinding
  Particularly in closed circuit operations, attention to the entire circuit, not just the mill must never be minimized. An improperly or inadequately maintained dust collector or separator can severely disrupt circuit capacity and product quality, and consequently specific power consumption.
  The particular aspect of a closed circuit is the mill feed which is made partly of fresh (new) feed and partly of rejects from the classification operation. The circulating load (ratio of rejects to fresh feed) is in most cases the operating parameter which governs the quality of the finished product. It ensures an homogeneous final product by absorbing any variation of the mill feed. In dry process, the circulating load is followed up by the mill

5.0 OPTIMIZATION (cont'd)

5.2 Grinding (cont'd)

- discharge elevator kW, which gives an indirect reading of total flow (mill throughput thus circulating load). The other chief operating parameters related to the circulating load are mill sound levels and feed measurement devices (weight feeders, electronic scales).

  Figure 31[28] summarizes the range of operation of size reduction methods.

5.3 Process control

5.3.1 Crushing operation controls (7 to 12)

The aim in crushing plant control is to ensure the utilization of most of the available energy. Crushing power is more energy efficient in terms of reduction than that used for milling. Crushing unit costs represent approximately 20 - 25% of the total comminution costs, against some 80 - 75% for milling. Crushing units are normally run in either one of two modes:

- Maximum reduction to be imparted to feed for subsequent processing. For that maximum energy per unit of feed is the operating criteria.
- Maximum quantity of a given sized product. For this mode, no more energy than that necessary to reduce material to the required size should be applied if production costs are to be minimized.

Both of these operations can be accommodated by a proper instrumentation and logics. Fig. 30 shows an example of an automated crushing plant. The principal elements besides the crushers and screens are:

5.0 OPTIMIZATION (cont'd)

5.3 Process control (cont'd)

(i) A variable rate feeder to adjust the feed rate into the plant.

(ii) Cumulative weighers to totalize the plant output.

(iii) A computer that accepts data from the plant, compares this with a set program, makes appropriate adjustments to the plant feed rate and affects balance adjustments to circuits within the plant.

(iv) Crushers are fitted with automatic setting regulation control systems so that the power rate of the crusher can be optimized allowing each crusher to draw maximum power on its available feed.

Hence, circulating load in the closed circuit and the classifying screen area will be minimized. Such a control must be preceded by a logic.

The following example supplied by Flavel will illustrate a case: (see Fig. 26 and Fig. 27).

The production program calls for 100,000 tons of mill feed to be produced in a crushing plant, in a planned period of 20 hours. The crushing plant comprises two stages with 2500 HP each. The total energy available is then:

2500 x 2 x 20 = 100,000 HP h or 74600 kWh

The hourly feed rate is:

100,000 Mg/20 h or 5000 t/h

If initial feed contains 25% of suitable fine product, the primary crushing operation will then be limited to 3750 t/h (assuming that screening is 100% efficient) after the first scalping stage. In case of finer initial feed, the proportions would be 1750 t/h for crushing and 3250 t/h being removed as product.

5.0 OPTIMIZATION (cont'd)

5.3 Process control (cont'd)

Considering that the scalping screen apertures are fixed, there will be a different quantity of feed directed to the various stages of crushing. The way of compensating for this problem is to use a variable setting control for the crushers. The proportions of incoming feed to each stage can be optimized by a computer program controlled by bin levels and the loading on various crushing machines. The computer adjusts the loadings in the plant so the power applied to the material is maximized or is at a predetermined rate.

L. Mollick (20) proposes two different circuits: a first one in open and single stage crushing, and a second one in closed circuit with two crushers. (See Fig. 29-1, 29-2)

5.3.2 Grinding-classification operation controls (13)

Because the two functions are usually interdependent, grinding and classification should be considered as one process in terms of instrumentation and control.

Horst and Enouchs (14) propose the example of a multistage wet grinding system that incorporates a rod mill followed by two ball mills in series.

For optimal control it is necessary to take into consideration definition of the controllable variables in the grinding circuit, available sensors that may be used to detect changes in the grinding circuit operation and techniques for controlling the process variables to compensate for disturbances in the grinding circuit operation.

Potential control objectives could be as follows:

1) maintain a constant grind size at maximum throughput,
2) maintain a constant feed rate within a limited range of grind size

5.0 OPTIMIZATION (cont'd)

5.3 Process control (cont'd)

3) maximize productivity per unit time in conjunction with downstream performance.

Usually there are economic constraints on the product particle size. Particles that are too large or too small lead to a reduction in efficiency.

The following measurement can be controlled in grinding circuit : feed rate, water feed rate (at different locations of the flow sheet), mill power draw, mill bearing pressure, mill sound, classifier feed rate, density,and classifier product particle size. The feed rate and water feed rate can be varied independently. Because the other variables depend upon and respond to changes in the fresh feed and water feed rates, control of the grinding circuit is achieved by manipulating these two feed rates. Introduction of a variable speed pump in hydrocyclone classification would introduce another degree of freedom in control strategy.

In the example (See Fig. 30) of Lynch (18) reported by W. E. Horst and R. C. Enochs of a wet grinding circuit with a rod mill followed by two ball mills the control objective is to stabilize the operation and to maximize tonnage throughput at a predicted particle size. These objectives are achieved by controlling the rod mill feed water - and thus the discharge density, the cyclone feed-pump sump level, and the water additions to the cyclone feed-pump sumps - to maintain the circulating loads at maximum power draw.

In very fine grinding of a circuit comprising mills and classifying systems the objective may be to maximize a certain particle size fraction while maximizing the hourly production. In addition to the conventional controls and feed rates control, mill and classifier powers, classifier settings etc., it is now possible to have

5.0 OPTIMIZATION (cont'd)

5.3 Process control (cont'd)

a particle size analyser on-line so that the granulometry of the product at any given location of the flow sheet is continuously followed up. This granulometer cumulates a sample within two minutes and gives the passing at several size cuts. It also calculates the specific surface. If needed, this specific surface may be correlated to the Wagner or Blaine Standards.

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION

In industries such as mining, cement and ore benefication there have been a progressive increase in the size of crushing and grinding plants. This increase in size and capacity is aimed at the reduction of the grinding cost per tonne of product.

In view of the present high power ratings of drives, it is therefore necessary to take a closer look at the efficiency and energy consumption of an electrical drive as a mean to reduce the cost of size reduction per ton of material produced.

6.1 Electric Motors

In a grinding or crushing plant, several electric motors are needed for driving the many and varied machines, material handling appliances, etc. The majority of these are simple three phase, A.C. squirrel cage motors. These motors have efficiencies that could range between 77% to 91% while the power factor ranges between 75 to 90% lagging.

High voltage (4.1, 6.6, 13.8 kv) synchronous or slip ring motors are used in situations where particularly difficult starting conditions exist or where the size and power rating of the drive necessitates limiting the starting current.

Also, the synchronous motor is more efficient than induction motors of the same size and is useful when running in the overexited condition to improve the power factor of the whole plant.

6.2 Motor Efficiency

Efficiency is an important factor in the selection of an electric motor.

Efficiency is higher for larger horsepower ratings and for higher speed ratings. However, where possible, over-motoring a drive should be avoided since a motor operating far from its full load range will lose on its efficiency (see Figure 33).

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION (cont'd)

6.2 Motor Efficiency (cont'd)

Typical efficiencies of synchronous and induction motors are shown in Figures 34 and 35. The unity power factor synchronous motors is generally 1 to 3% more efficient than MEMA design B induction motors of the same ratings.

The 0.8 pf synchronous motor, because of the increase in its losses, its efficiency is closer to the induction motor at high speeds, but better at low speeds. However, a synchronous motor with 0.8 pf leading will serve the dual purpose of providing power and improving plant power factor.

The following table outlines a comparison between different types of a mill drive rated 6500 HP, 514 rpm.

Type	Inrush	p.f.	Eff.	Cap. Cost
1. Syn. motor with clutch	250-325%	0.80 lead	97%	100%
2. Syn. motor w/o clutch	625%	0.80 lead	96.5%	125%
3. Squirrel cage motor	650%	0.87 lag	95%	100%
4. Wound rotor motor	175%	0.87 lag	95%	200%
5. Gearless motor (15 r/min) with Cyclo-converter w/o mill gears	200%	1.0	91%	500%

An advantage of 1% efficiency at $0.03/kWh for 6500 HP operation amounts to about $10000/yr energy.

Comparing the drives type 1 with 3, having the same capital cost, savings in operating cost of $20000 per year could result if drive type 1 is selected since it is 2% more efficient than the wound motor:

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION (cont'd)

6.3 Voltage Drop

The following table outlines the general effects of voltage variation on the performance of an induction motor.

	Voltage at 90% V Nominal	Effect
Starting TORQUE	decrease 19%	- increase starting time - increase voltage drop for large machines
Starting current	decrease 10%	- increase motor heating
Maximum running TORQUE	decrease 19%	
Percent Slip	increase 23%	- reduce capacity of screw conveyors etc.
Efficiency at full load	decrease 2 points	
Power factor	increase 1 point	
Full load current	increase 11%	- bad efficiency due to increased cooper loses - reduce motor life

Voltage drop exceeding 6% can be reduced by:

- paralleling cables.
- use of tap changers on transformers.
- use of voltage regulations.
- changing the configuration of the distribution system.
- correct power factor of load stations and large induction motors.

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION (cont'd)

6.4 Power Factor

The ratio of actual power (kW) to apparent power (kVa) is an important consideration in plant electrical distribution system.

Good power factor results in lower system losses, better voltage regulation, reduced power costs and increased system capacity.

One of the chief causes of poor power factor is lightly loaded induction motors (Figure 37). Also, other inductive loads such as transformers and cables contribute to lagging power factor.

On the other hand, capacitors and synchronous motors create leading power factor.

For large drives such as for grinding mills, it is recommended to select synchronous motors running at unity power factor. These motors offer better efficiency and do not contribute to the lagging power factor of the grinding plant.

Using overexcited synchronous motors to correct a plant power factor means that the correction depends on the operation of the mill motor, i.e. poor power factor has to be accepted during periods of mill shut down.

Individual p.f. correction by means of capacitor could be provided to other high voltage motors such as crusher drive motor or separator motors. These capacitors are connected to motors terminals and are switched with it. However, power factor correction beyond 95 is not justified.

At load centers where many low voltage squirrel cage motors are connected, the resultant power factor is low. The best solution to correct this power factor is to connect automatic capacitor control unit to the switch gear.

6.0 ELECTRICAL POWER SUPPLY AND CONSUMPTION (cont'd)

6.5 Improvement of Electrical Energy Consumption

As a summary and apart from improving the process itself, the means to reduce the cost of electrical energy consumed in a comminution process are outlined as follows:

- Efficient utilization of electric motors, either by using high efficiency motors at premium cost, or by reducing the time during which the motors are running at no load or reduced load (avoid sustained reduction in production capacity).

- Eliminate excessive voltage variation at the motor terminals by reducing the voltage drop in a grinding and/or crushing plant.

- Utilization of highly efficient synchronous motors with unity or leading power factor for large drives such as at ball mills motors.

- Utilization of capacitors for power factor improvement at large induction motors such as gyratory or hammer crusher drives and at main motor load centers.

- If possible, reschedule the operating times of the machines to avoid peak hours or reduce the peak or average demand of the plant.

  Also, the peak demand should be monitored to avoid penalties and automatic tripping of certain machinery should be done whenever a certain demand is reached.

7.0 FINDINGS

7.0 FINDINGS

- There exists abundant of published work on relationship of energy consumption to size reduction. The validity of various methods for defining these relationships has been compared and reviewed.

  In general, the proposed relationships are only valid over limited ranges of variables in specific cases, as illustrated in Fig.3.

However, these relationships are not worthy applicable to the industrial scale because:

- The feed material is not homogeneous
- The actual specific power consumption in any crushing or grinding unit, can not be explained only be the feed characteristics and the output fineness. The comminution work results from several functions among which are the breakage function, the selection function, the transportation function. All these functions participate under unknown proportions to the final energy consumption. Moreover, these functions may not be considered as independent and their interaction calls for very elaborated simulations.
- It is only a small fraction (less than 3%) of energy consumed is actually used for the breakage operation. The remaining 97% is dissipated into heat (85%) sound and media wear.

SNC

It may be concluded that size reduction is an indirect result of energy consumption as expressed by Lynch (18)

Large particle + energy ——→ smaller particles + heat + sound

Hence, what all these laws have in common is that they can at least give informations on the physical work done in effecting the size reduction, but not on the actual power consumption which is of interest in connection with comminution machinery.

7.0 FINDINGS (cont'd)

- Most of the grindability laboratory tests refer to a specific industry. They may not be considered of universal implementation. Study of particular sets of testing data from reported observations are often valid for that range of industry at most.
  Since each grindability test refers to a given industry, it also refers to a given grinding circuit type. As it has been seen, some grindability tests are based on a circulating load simulation whereas others are simply performed on an open circuit philosophy.
  However, there is no doubt that any grindability test is useful but after having been scaled up for each case. Grindability tests are very interesting when comparing two different coals to be size reducted in the same full scale grinding unit, for instance, or two different cement clinkers i.e. when one needs to predict the output, in case of feed characteristics changes, in terms of Kwh/t as well as in terms of finished product particle size quality.

- There is no major problem of measuring the crushed or ground product. More and more apparatus available on the market today provide very good performances and may even be installed on line in a full scale grinding unit.

- Comminution machinery varies both in size and in reduction ratio. A proper selection is the chief factor in optimization. The selected machine must cope with the feed characteristics, particularly its moisture content and abrasiveness, and the product granulometric distribution. Under the specific power consumption viewpoint, two machines seem to be more efficient: impactor-type for crushing operation, and roller mill for grinding circuit. Unless ruled out because of feed constraints, they offer a good quantity-quality relationships. For very hard, abrasive or sticky material, there is no choice but to select conventional machines: jaw-gyratory type crushers, tumbling mills. As to the autogeneous type machine, it is

7.0 FINDINGS (cont'd)

- being abandoned because of its high power demand.
- Because grinding is generally performed in dry closed circuit, any analysis of the equipment performances should take into consideration the classification stage. Air separators are far from being efficient. They systematically reject an important part of fines as tailings, decreasing drastically the grinding unit effectiveness.
- New methods of comminution are being investigated but they cannot be considered for the short or even medium term. On the other hand, new mill types are being presently studied; planetary ball mill, slant mill and vibrating mill. It is too soon to predict which one will be the most suitable and reliable for the industrial use.
- Once crushing and grinding systems are selected, the second topic not to be neglected is the maintenance program. It is recognized that in many cases when an action is taken on the process, the positive results obtained are explained for a good part by the series of small calibrations or adjustments which accompany this action. For examples: feed measurement devices, wear parts, classifier settings, venting, dust collector efficiency, grinding aid system of injection, waterspray. A 5% increase in the efficiency of the installation is not uncommon.
- With regards to the process, comminution operations suffer from the circulating load problem. Although closed circuit systems consume less energy than opened circuit systems, the "law" does not hold true, beyond a certain value of recycled material.

  Circulating loads in dry grinding (cement milling for example) may be as high as 1000%, which means that the mill throughout is constituted by a proportion of fresh feed to recycled material (tailings) of 1 to 10. Use of high circulating loads (500% is common in cement grinding today) is the only way to avoid fines in finished produce, since air separator efficiency is low.

7.0 FINDINGS (cont'd)

- Circulating loads optimum are different from plant to plant and generally result from a series of field trial and error experiments.

- Consequently, the area to be investigated for optimization is the separation stage. To take into consideration this aspect and dry grinding, the idea of having two separators in series deserves a special attention. The principle is that the tailings from the first separator are conveyed to a secondary separator for a second classification. As a result, the finished product will present a much steeper granulometric curve and the gain on the overal specific power consumption may be estimated to 5% for an increase in production of approximately 10 - 15%.

- The process control in crushing as well as in grinding is based on the assumption of a common objective which may be different from industry to industry; then an optimization criteria is determined to which all operating parameters are related. Once the criteria for the optimization has been established, it is relatively easy to implement the defined process logics, based on existing instrumentation. The finished product characteristics can be achieved by the use of available on-stream x ray fluorescence analyser and particle size analyser. The latter can give actual particle size distribution of the product along with all statistics. These two devices can greatly help the operator in actually optimizing his installation by following up more than one characteristic (in chemistry as well as in granulometry) of the finished product. This possibility will allow not only to optimize the kWh/t of the comminuted product, but the kWh/t of the valuable part of the comminuted product.

7.0 FINDINGS (cont'd)

- Automation strategies for energy conservation in comminution may be classified into four major thrusts:
  i. Control of individual elements of comminution to maintain uniform operation at some chosen performance index.
  ii. Elimination of product recycling where possible.
  iii. Determination of target performance indexes for individual elements of comminution such as to optimize the overall system performance even at the expense of the energy efficiency of some elements.
  iv. Monitoring of key process parameters and recording of performance indexes to facilitate intelligent analysis and selection of alternate optimum operating strategies where these cannot be computed automatically.

It goes without saying that a prerequisite to any active automation scheme is a controllable process. That is, a process where a parameter can be automatically regulated in order to influence the process in the desired manner. Failing such a condition, passive automation may be implemented. That is, strategie parameters may be monitored which will give the operator the information necessary to advantageously manipulate process adjustments.

Due to its very nature, blasting cannot be extensively automated. At most, mine/quarry operations planning and analysis can be computer assisted. As stated earlier, the function of blasting is to prepare material for crushing. Thus, the objective is to produce rock of uniform maximum size consistent with crusher inlet and transport capacities. Boulders that need secondary blasting and excessive blasting that shallows more than required constitute energy wastage.

7.0 FINDINGS (cont'd)

Traditionally, the objectives of crushing and grinding were basically the same, i.e. to produce the maximum rate of on-spec material. If energy conservation in the overall comminution chain is the objective, then the goals of the individual element must be modified recognizing the contribution that each makes. Grinding is the largest energy consuming operation in the chain. However, since its objective is final product quality, the only degree of freedom available in terms of energy conservation are the reduction of unnecessary product recycling and control of input feed quality. Crushers are like most energy efficient elements of the chain. Thus, it may be advantageous to operate them at less than peak energy efficiency and over-crush to save on grinding costs.

Once a grinding method is selected, there are basically three parameters that can be regulated that will effect energy efficiency other than the maintenance aspect. These are the crushing medium adjustments, the feed rate and the feed quality. Efficient crushing depends upon the transfer of the maximum amount of energy that equipment can deliver to individual ore blocks. This maximum work is obtained from crushers if they are automatically readjusted to draw maximum specific power, that is, power per tonne of ore crushed.

To date, only cone crushers have been successfully automated in this way by hydraulically adjusting the crushing gape. Feed rate should be controlled to maintain a uniform rate, normally set at the same value as grinding throughput. Alternatively, if the crushing capacity is rated higher than grinding, another degree of freedom may be available. Feed rate can then be trimmed to obtain desired product size. For instance, feed may be increased more than the crusher optimum, thus, in effect, cushioning impact forces and initiating some grinding

action in order to reduce the amount of treatment required in the grinding circuit. This latter strategy is particularly useful as a compensation of varying grindability of ore. It is more energy efficent to over-crush harder ore, since otherwise, the energy penalty in the grinding circuit would be considerably higher.

As stated previously, the objective of the grinding circuit is to produce a product of the desired quality. Conventional control schemes perform adequately. Energy conservation opportunities are mainly in the elimination of re-grinding of material through efficient classification and the prompt evacuation from the circuit of ground product.

8.0 CONCLUSION & RECOMMENDATIONS

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The optimization of any comminution system is dependent on the following:

- Equipment selection: Each piece of the size reduction circuit must be properly selected in accordance with its input and output in such a way that the whole comminution chain constitutes a single and continuous system.

- Constant operating parameters selection: Certain parameters cannot be adjusted while the circuit is running. These variables, which are thus transformed into constants when the installation is in operation, must be properly fixed to respond to an average of a normal run such as:

  - ball load volume and gradation in a ball mill
  - number of selecting and/or fan blades in an air separator.

- Variable operating parameters selection: These variables deal with process control. Any eventual change in the feed characteristics must be automatically absorbed through the various equipment adjustments so that finished product properties are maintained to the required objectives.

Until recently, optimization has been achieved exclusively by full scale experimentation and this has proved to be a reliable method. Though it often leads to trials and errors, never-the-less, it has always resulted in very substantial gains in product quality as well as in the capacity for a given comminution circuit with a significant specific power consumption savings. However, these findings are rather of qualitative than of quantitative nature. Saving in the energy differ from industry to industry from one installation to another.

8.0 CONCLUSION & RECOMMENDATIONS (Cont'd)

Taking into consideration the demands of the market calling for an increasingly high quality product and energy savings, the following recommendations for comminution optimization is made:

- Extension of the crushing range since crushing is less energy consuming than grinding.
- Increase of the efficiency of the separation stages in order to avoid excessive material recycling. If necessary, multistage separation must be forecast.
- Definition of a process control strategy for each case. Its implementation as far as instrumentation is concerned does not present any major difficulty.

9.0 RECOMMENDATION FOR FURTHER WORK

9.0 RECOMMENDATION FOR FURTHER WORK

The application and importance of the industrial minerals in the three major sectors of the Canadian economy vis-a-vis construction, agriculture and industrial requires that the study of energy conservation in comminution process be undertaken separately for each of the sectors. This would result in better understanding of the potential of optimization comminution processes for the various industries. To achieve this, it is recommended that the following studies be carries out:

(i) conventional aggregate preparations
(ii) potash processing
(iii) Asbestos ore benefication

The scope of the above studies should include the following:

- Flow-sheet and specification of finished products: this should include not only the end-products but also intermediate products at various grades.
- Comminution technology:
  - Machinery: definitions and performances of machines used
  - Circuits: definitions of various arrangements
    study of classifications/separation stages
- Comminution operation control:
  - Traditional practices
  - Automation
- Simulation approach: review of the available techniques and extent of application potential in comminution process for each of the above mentioned topics.
- Optimization: steady-state operation - specific power consumption vs quality of finished products.

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APPENDIX A

REVIEW OF INDUSTRIAL ROCKS AND MINERALS

The description, properties, and uses of several industrial rocks and minerals are presented here [1] [3]. These include:

- Asbestos
- Barite
- Gypsum
- Limestone and Dolomite
- Potash
- Salt
- Sand and Gravel
- Elemental Sulphur

REVIEW OF INDUSTRIAL ROCKS AND MINERALS

ASBESTOS

DEFINITION

Asbestos is an economic term, based on a common property, applied to all the fibrous minerals.

About 95% of the asbestos production consists of the mineral Chrysolite.

Chrysolite is a fibrous form of serpentine, a hydrous magnesium silicate: $3MgO.2SiO_2.2H_2O$.

PROPERTIES

The outstanding physical characteristic of asbestos is its fibrous structure. Asbestos fibers possess high flexibility with lengths ranging from only about 1/4 to 3/4 inch.

Asbestos fibers are noninflammable and heat resistant to about 260°C. Two varieties, crocidolite and anthophyllite are strongly resistant to acids.

USES

Two classes of asbestos are recognized on the basis of use:

Spinning fibers: include the longer grades of chrysolite and crocidolite. Spinning fiber is made into asbestos thread, yarn, tape and cloth.

USES (cont'd)

Nonspinning fibers: consist of the shorter grades of chrysolite and crocidolite and all grades of amosite and anthophyllite. Nonspinning fiber is mostly used in compressed, molded, or cast products in which the asbestos make up a felted mass in a binder such as Portland Cement.

BARITE

DEFINITION

Barite is natural barium sulfate, $BaSO_4$. Its distinctive features are: high specific gravity, 4.3-4.6 and a large range in hardness, 2.5.-3.5 on the Mohs Scale.

PROPERTIES AND USES

Drilling for oil and gas requires a heavy circulating fluid to control the reservoir pressure. Ground barite used in oil and gas wells accounted for 95% of the total U.S. 1980 sales.

Barite serves as a source of barium chemicals and it is used in several other industries such as: paint, paper, rubber, plastics and glass.

In ground form, barite is used directly as a filler chiefly in rubber and as a paint extender.

GYPSUM

DEFINITION

Gypsum is hydrous calcium sulfate, $CaSO_4.2H_2O$. Anhydrite, $CaSO_4$ occurs interbedded with gypsum and may be partly used, in some industries, as a substitute for gypsum.

PROPERTIES AND USES

The chief use of gypsum covers the plasters industry. When heated to about 175°C, gypsum loses 3/4 of its interstitial water to give the semi-hydrate (calcinated gypsum or plaster), $CaSO_4.1/2\ H_2O$. Calcined product represents upto 70% of the total production of gypsum, including the gypsum for dry wall board. The finest grades of white gypsum plaster are used in special applications in the ceramic, molding, dental and sculptor industries.

Uncalcined gypsum is required in:

- cement manufacturing to retard setting time of the cement
- agriculture as conditioner and fertilizer.

Small amounts of uncalcined finely ground gypsum are used as insecticide carrier and filler.

EXTRACTION AND PROCESSING

Overburden stripping is followed by the standard operations in quarry development. Underground mining is not so important.

EXTRACTION AND PROCESSING (cont'd)

After having been crushed and screened to the proper dimension, raw gypsum may be sold without further beneficiation to the Portland Cement industry or for application to the soil.

As for the calcined gypsum, the product undergoes a milling process. Plaster or finished product - may contain additives - retarders, accelerators - for the processing of gypsum dry wall boards.

LIMESTONE AND DOLOMITE

DEFINITION

The term limestone includes those sedimentary rocks made up of 50% or more of the minerals calcite, $CaCO_3$ and dolomite, $CaCO_3$ $MgCO_3$. The proportion of combined carbonates in most commercial limestones is 90% or more.

The high-calcium limestone contains at least 95% of calcite. The high-purity dolomite contains more than 97% total carbonates, practically all being mineral dolomite.

PROPERTIES AND USES

Physical Properties

Uniform, nonporous and free from chert, organic matter, limestone (or dolomite) makes a tough, sound aggregate and stands up well in other types of services. It is less abrasive to crushing equipment than other commonly used types of stone (granite, sandstone, etc.) Limestone is also used as a dimension stone. It must then meet the same requirements as for other types of dimension stones (granite, marble, sandstone): uniformity of color and texture, freedom from iron sulfide - which may oxidize to form a stain - and absence of quartz which make working of the stone difficult.

Chemical Properties

As raw material for cement: the raw material for cement manufacture must include lime, silica, alumina and iron oxides. The ideal cement rock often called natural cement is an impure limestone with these oxides in just the right proportions. The scarcity of natural cement

Chemical Properties (cont'd)

lead to the use of the silico-aluminate rocks, clay and its derivates along with limestone to produce properly balanced cement raw mix.

The most stringent requirement of limestone is a sharp limit in its magnesia content which may not exceed 3%. This rules out the use of dolomite limestone.

As fluxstone: in the smelting process, iron ore impurities (silica and alumina) are removed by the addition of limestone or lime as a basic flux. Silica, alumina and eventually sulfur from the coke combine with the flux and form a liquid slag. Since this slag contains the four major components required for the cement manufacturing, i.e., SiO_2, Al_2O3, Fe_2O_3 and CaO, cement manufacturers use it quite often as a raw material.

As sources of lime: when heated, limestone and dolomite loose carbon dioxide and yield lime. The temperature required is 1000-1100°C. The heating of pure limestone, $CaCO_3$ yields 56% of lime (CaO) by weight.

Unlike the hydrated lime, $Ca(OH)_2$, which is a stable form, the Quick Lime which comes from the kiln has a strong affinity to carbon dioxide.

In the construction industry lime is used in plaster and mortar, and in soil stabilization. Lime is also used in agriculture.

Additional properties of dolomite: dolomite or dolomitic limestone may be calcined at about 1500°C to give a partially sintered product called dead burned dolomite, CaOMgO which can withstand high temperature and is utilized as a refractory.

EXTRACTION AND PROCESSING

Limestone and dolomite for all uses except dimension stone are removed by conventional methods from quarries of the bench type. Stripping of overburden is followed by drilling and blasting.

Processing invariably involves crushing and screening, but preparation beyond this stage depends on the product granulometry desired - aggregate, cement and lime material, fluxstone.

POTASH

DEFINITION

The term Potash refers to potassium oxide, K_2O, and serves as a common denominator for the commercial comparison of all potassium compounds. The principle use of potassium salts is in fertilizers. The potash equivalents of several minerals are:

MINERAL	COMPOSITION	K_2O EQUIV.%
Sylvite	KCl	63
Langbeinite	K_2SO_4 $2MgSO_4$	23
Carnallite	KCl $MgCl_2$ $6H_2O$	17
Kainite	KCl $MgSO_4$ $3H_2O$	19

USES AND PRODUCTION

Agriculture remains the principal consumer of the potash minerals. About 95% of the production goes into the manufacture of fertilizer. The most widely used compound is a grade of potassium chloride having a K_2O equivalent of about 62%.

For agricultural use, the mined potash minerals are blended with other plant foods such as phosphates (P_2O_5) and nitrogen compounds.

High purity potassium chloride is the basic compound from which scores of different potash salts are obtained for use in the chemical and processing industries: soaps, ceramics, textiles and explosives.
In 1980, The Canadian potash K_2O production, one of the leading mining activity, totalled 7.2 million tonnes as shown on the next page.

NON-METALS	TONNES, 10^3	$ MILLION
Asbestos	1,323.0	618.5
Gypsum	7,336.0	39.5
Potash K_2O	7,201.0	1,020.7
Salt	7,423.0	122.8
Cement	10,274.0	581.4
Lime	2,554.0	129.2
Clay Products	...	108.4

SALT

DEFINITION

The chief component of common salt is sodium chloride, NaCl. In nature, it occurs in solid form as rock salt of which about 95% is the mineral Halite. The impurity in rock salt is mainly anhydrite, $CaSO_4$. The salt is extracted in the solid form by mining, or is produced as artificial brine. To obtain brine, wells are drilled into the salt, and water is pumped down to dissolve the salt. The brine may be evaporated to yield solid salt or used directly in chemical processes. Sodium chloride is also present in naturally occurring brines of various types such as: salt waters (sea, lakes, springs), porous rocks underground etc.

In Canada, salt from brines accounts for about 25% of the total production.

USES AND PRODUCTION

Salt is essential to the chemical industry. Most of the salt produced and consumed by chemical manufacturers is not utilized as such but is dissociated into sodium and chloride ions.

Salt is also used in the manufacture of soap and dyes, the processing of textiles and leather, dust and ice control, water treatment and metallurgy.

In the food industry, it is employed in refrigeration as a food preservative.

Canadian production of salt in 1980 was of 7.43 million tonnes for a total value of 122.8 million dollars.

SAND AND GRAVEL

DEFINITION

The term fine aggregate applies to sand or to sand-size crushed stone and coarse aggregate to gravel or to ground size crushed stone. There is also a difference in composition between sand and gravel. Quartz is the main component of sands, the latter being more noteworthy for uniformity than for variety. Gravels are more heterogeneous in composition, their dominant constituent being rock fragments rather than mineral grain. Gravel constituents may range from soft shale to hard and resistant granite or quartsize. Other rocks commonly present in the gravel are sandstone, limestone, dolomite and various volcanic rocks.

USES

When all the nonmetallics are ranked on a bulk volume basis, the sand and gravel aggregates constitute the leading group. Despite their low unit value, the Canadian production of sand and gravel in 1979 was the fourth most important nonmetallic industry after asbestos, potash and cement.

The construction and paving industries are the principal consumers of sand and gravel, the main use of both materials being as aggregate in concrete.

A small tonnage of sand is used as silica source in the glass industries or even in the cement manufacturing if there is a silica deficiency in the raw mix.

PROPERTIES

Sand and gravel differ from the other industrial rocks and minerals in being unconsolidated, highly variable mixtures of many constituents.

Unlike most of the other nonmetallics, sand and gravel are capable of being (easily) artificially upgraded, by such processes as screening, washing and combining of size grades.

PROPERTIES

The industrial requirements for the aggregates preperties are limited. Deposits used for aggregate must be free of organic matter. Small amounts of clay are tolerated if they can be subsequently removed by washing. Large proportions of silt (material passing a 75 micron sieve) is deleterious.

A good resistance to abrasion is important in the processing of aggregate of all uses. In this respect, the mixed nature of gravel may cause difficulty. Weak or crumbly rock is not tolerated, neither are fragments of friable sandstone, although their individual grains have the hardness of quartz.

Soundness is important and aggregate must have high resistance to freezing and thawing, and to wetting and drawing. Porous fragments cannot be accepted.

In regards to the particle shape, equidimensional, rounded particles are preferred because of a better concrete workability.

EXTRACTION AND TREATMENT

For deposits above the water level, excavation is by equipment common in the quarrying field, shovel, dragline, etc.

EXTRACTION AND TREATMENT (cont'd)

In wet pits or shallow streams, various types of draglines or dredges may be used.

Plant processing includes washing, screening, removal of undesirable matter and fines, and eventually crushing of oversize material. The plant is essentially a combination of conveyors, screens, crushers, and washing and classifying equipment.

ELEMENTAL SULPHUR

DEFINITIONS AND PROPERTIES

Sulphur (or sulfur) is a non-metallic element which has characteristic hardness of 1.5 to 2.5, a specific gravity of 1.9 to 2.1 and a melting point of about 110°C. Sulfur burns at 248°C. The mineral is insoluble in water and in nearly all acids. It is a very poor conductor of heat and a non-conductor of electricity.

SOURCES AND USES

There are several sources of sulphur, or of its chief derivative, sulfuric acid. In Canada sulphur is obtained from three sources:

- Elemental sulphur derived from sour natural gas, petroleum and tar sands.
- Sulphur recovered from smelter gases in the form of sulfuric acid.
- Sulphur contained in pyrite concentrates, used in sulfuric acid manufacture.

Most of the output is converted into sulfuric acid which is so indispensable in modern industry that its consumption is a reliable index of a nation's industrial activity.

About 60% of all sulphur is consumed in the production of phosphate and ammonium sulfate fertilizers.

PRODUCTION

In 1981, shipment of sulphur in all forms in Canada reached a record of 9 million tonnes for a value of more than $700 million. This makes the sulphur the second most important industry in nonmetallic production.

APPENDIX B

CEMENT MANUFACTURING

INTRODUCTION AND ROLE OF COMMINUTION

Cement manufacturing is, in general, a fuel and power intensive industry.

Comminution of raw materials and endoduct consumes more than 70 kWh per tonne of finished cement, depending upon the process used. Comminution in cement plants is important since a high degree of free surface is required in the raw mix so that the chemical reactions in the kiln could be completed in relatively short time. These chemical reactions result primarily in the dissociation of the carbonates to free CaO and MgO. Also it results in the combined water in the argilleous material. Finally the interaction between the lime and the silicates results in the formation of the four main mineral components responsible for the cement properties such as setting time, heat of hydration, expansion, early and final resistance to compression and tension, and resistance to sulfates.

Comminution is also required to reduce clinker size, mixed with 4 to 6% of raw gypsum, to obtain cement as final product. In fact, a highly reactive free surface is required in cement to react with water during hydration and to allow for a reaction between clacium sulfate and cement hydrate to retard the setting time and then to achieve the early and final hardness according to the specification. The fraction between 5 and 40 microns is the most reactive and contributes to the strength in cement and concrete. It is also known that a higher fineness in cement cuases a greater shrinkage. Also, another phenomenon to be noticed is that only 54% hydration is achieved on cement grains exceeding 5 microns.

PROCESS

There are four main stages in the cement manufacturing process and these stages are; the preparation of raw materials, the proportional drying and grinding of the raw mix, the burning and cooling of clinker and finally, the finished cement grinding.

Blasting is the first size reduction for each raw material. In dry process, after being crushed, the raw materials are mixed directly or are premixed. Then, they are dried and ground in mills to a fine powder with a maximum residue of 14% on the 200 mesh sieve (75 microns). Additives, such as iron oxide and/or sand, are mixed in small amounts to the grinding mill feed. The mill output is then homogenized and corrected in homogenizing silos. In the wet process, the raw mix preparation is all carried out in a wet state (slurry). In the rotary kiln, the raw mix or the slurry is burned into clinker which is finally mixed with raw gypsum in the final cement grinding operation.

Finished product cement (normal type) should comply with the following C.S.A.* requirements:

- Chemical requirements	Loss of ignition	LOI = 3.0%	max.
	Insoluble residue	Ins.= 0.7%	max.
	Sulphur trioxide		
	if $C_3A > 8.0\%$	SO_3 = 3.5%	max.
	if $C_3A \leq 8.0\%$	SO_3 = 3.0%	max.
	Magnesium oxide	MgO = 5.0%	max.
- Physical requirements	Passing at 75 micron Sieve	82%	min.
	Soundness = expansion	1%	max.
	Setting time, minutes	45	min.
		36.5	max.
	Compressive strength, MPa		
	at 3 days	12.5	min.
	7 days	18.0	min.
	28 days	26.5	min.

* Canadian Standards Association

COMMINUTION EQUIPMENT IN CEMENT PLANTS

Blasting

Blasting could be considered as a way of reducing size of the raw materials. In fact, it reduces big masses of rocks into smaller sizes which do not generally exceed one cubic meter. Higher fragmentation using a higher proportion of expensive explosives can achieve, at the following crushing stage, a more valuable saving in power energy.

In cement plant quarries, rotary drills are used for drilling bore holes whose diameter vary between 2 and 6". Distances between bore holes vary according to the rock uniformity and characteristics but also to the drill hole diameter and explosive loading. The bore holes are alternatively loaded with explosives and stemming material. The AFNO type of explosive is generally used with a booster at a powder factor of 100 to 150 grammes per tonne. In cases of chalky material and clays, no blasting is needed; the material can simply be ripped.

Mining of clays is done by different methods depending upon its physical characteristics. In very rare instances are explosives used but only in very small amounts and just to disintegrate the rock. In most cases, clay is ripped or extracted directly by front end loaders or hydraulic power shovel.

Crushing

In cement raw materials preparation, crushing consumes approximately 3 kWh/t of material.

Crushing is performed in one or more stages depending upon the final size distribution required from the product. In case a part of the product is to be sold as aggregate, more than one crushing stages are used in order to obtain the various particle sizing complying with the aggregate specifications.

COMMINUTION EQUIPMENT IN CEMENT PLANTS (cont'd)

Crushing (cont'd)

Usually, crushing is done in one stage when the material is to be used for cement making.

The equipment used for this operation is as follows:

- Multistage crushing: Primary gyratory and cone crushers,
- Single stage or secondary crushing: Jaw crushers, hammer crushers or impact crushers for limestone type rocks.
- In case of plastic clay: Non-clog hammer crushers, single (toothed) roll crusher is generally used. If needed, a heating system may be included in the crusher.

Impact and hammer crushers (or hammer mills) are more and more selected because of their very high reduction ratio, averaging 30 to 1.

Sillem[27] reports a reduction ratio of 50 to 1 in case of hammer crushers. They can handle material with 10 - 15% moisture content, with a slight advantage over the impact crusher. However, hammer crushers can be fed simultaneously with a mixture of hard dry limestone and a plastic clay containing substantially more moisture.

As in regards to rock abrasiveness, upto 10% free silica is allowed in the raw material fed to impact crushers but only 5 - 6% in the case of hammer crushers.

Unlike grinding machines and because of a wide range in reduction ratios, comparison of crushers in terms of kWh/t consumption should be approached carefully. However, some figures are reported by Sillem (27):

	Gyratory	Impact	Hammer
Reduction ratio	5 - 8	6 - 20	40 - 60
Installed kWh /t	0.15 - 0.3	0.7 - 0.8	1.5 - 2.0

COMMINUTION EQUIPMENT IN CEMENT PLANTS (cont'd)

Crushing (cont'd)

Impact-type crushers are gaining more attention compared to the conventional jaw and gyratory types. Unless ruled out by the properties of the raw material, they are capable to reduce, in a single pass, pieces of rock of 1.5 m feed size to 25 mm product size suitable for feeding conventional ball mill.

In dealing with hard and abrasive materials, size reduction by compression is more favorable. Gyratory type crusher is used. But in this case, two or three crushing stages are required because of the low reduction ratio as compared to the impact and hammer crusher types.

Classifying equipment such as vibrating screens is needed, if for example, some of the product of an impact crusher consisting of oversized pieces have to be screened out (scalped) and returned to the crusher for further size reduction. Furthermore, feed to impact crusher is often previously screened in order to relieve the machine from fine material.

Raw Grinding - Dry Process (see Table 5)

Aerofall Mill (Autogeneous)

Aerofall mills are not proposed any more in cement plant design being considered as energy intensive. The fan for the air sweeping system consumes a prohibitive amount of power.

Ball Mills

In raw grinding, ball mills most often used are single and multi-compartment mills, airswept mills, double-rotator mills. In general, they are coupled with an external classifying system (air separator).

Ball Mills (cont'd)

Until recently, they were considered as being the only mills capable of generating high specific surface for cement manufacturing. At high fineness (above 300 m^2/kg), closed circuit is more advantageous than open circuit in terms of kWh/t. Although compound mills and short mills consume less power than airswept mills, they all are more power intensive than roller mills. From the drying aspect, they usually cannot handle feeds higher than 10% in moisture content. They must be continuously operated at full capacity. In practice, when feed size exceeds 1", the performance drops drastically.

The main advantage of ball mills is their undeniable capacity to grind hard materials, though they are less sensitive to free silica than other mill types. Ball mills are robust and reliable but require large structual supports.

As described in a previous chapter, the drying operation is performed either in the mill or in the separator. See Figures 38 and 39.

Roller Mills (see Figures 21 and 40)

Roller mills are the most efficient grinding machines in the cement industry [26]. They adapt very well to most cement raw materials.

Compared to conventional ball mills, they consume 20 to 30% less kWh/t (see Table 6).

The drying operation as well as the separation work is carried out in single stage operation. Factors limiting their performance are:

- Sensitivity to tramp iron.
- Sensitivity to highly abrasive materials. Feed should not contain more than 5% free silica.

COMMINUTION EQUIPMENT IN CEMENT PLANTS (cont'd)

Roller Mills (see figures 21 and 40) (cont'd)

Roller mills advantages may be summarized as follows:

- Low specific power consumption
- Feed size up to 3½"
- Easy to automate and control
- Relative high drying capacity
- High degree of reliability
- Low noise level
- Less capital intensive
- Short retention time thus no overgrinding, no particle reagglomeration
- Possibility to be operated at fractional capacity.

Roller mills are replacing more and more conventional ball mill systems in cement raw meal preparation.

Effect of Finer Stone Pre-Crushing Before Ball Milling

Ball mills are generally operated in closed circuit. Depending on the circulating load values, fresh feed may represent half of the total mill feed (if circulating load is 100%) or 1 to 10% of the total mill feed (if circulating load is 1000%). Because of this lack of uniformity in the mill feed, the grinding balls cannot be continuously adapted to the material. This results in undergrinding or large particles in the first compartment or overgrinding of a large part of the material being ground, depending upon the method of calculating the ball load gradation.

On the other hand, crushing operates within a size range whereby particles are being processed individually and fine product rapidly removed from the breakage zone.

COMMINUTION EQUIPMENT IN CEMENT PLANT (cont'd)

Effect of Finer Stone Pre-Crushing Before Ball Milling (cont'd)

The problem is to select the crushed product size to be fed to the mill. Literature[24] reports that up to 6% energy savings may be expected once the proper maximum lump size has been determined by crushing over sized material before it enters the mill.

This field of potential energy savings is being investigated and results may be very encouraging.

Raw Grinding. Wet Process (see Figures 41-42)

Cement manufacturing by the wet process is practically being abandoned, except when raw material moisture content is high, such as in the case of soft chalk with 22%, sticky clay with 26-30% of natural water (as quarried). In general, wet grinding consumes less power than drying and grinding by applying closed-circuit arrangement. LESNIAK[17] estimates it to 30% less. Classifying operation is mainly achieved by curved screens called DSM* screens whereby the slurry is admitted through a nozzle and impinged on the cylindrical inner surface at high velocity. Because the aperture size is about twice the particle cut size, high screen loadings are possible without risk of choking or blinding the screen.

In wet process, grinding media and liners undergo wear not only by abrasion but also by corrosion. To counteract this excessive wear, grinding ball manufacturers propose alloys containing 30% chromium. As for the liners, (according to the reports by SILLEM[27], those made of rubber have demonstrated a useful life of about three times as conventional linings.

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* DSM is an abbreviation of DUTCH STATE MINE

Clinker Grinding (see table 7 and figure 43)

Clinker grinding is generally performed in ball mills; single or multicompartment (up to three). The most frequently encountered installation is the tandem two compartment mill and air separator in closed circuit. To date, Roller mills were not used for clinker grinding due to its abrasiveness. However, research is being carried out to solve this problem in order to benefit from the numerous advantages of the Roller mill, including power consumption.

Cement grinding is one of the best examples where the notion of kWh/t is so tied to the quality of the material. Even when the complex problem of marketing in the North American competition is not taken into account, there is no doubt that a fraction of finished cement is unnecessarily ground to an exaggerated fine grain.(19)

Indeed, CSA and ASTM physical requirements ask for a specific surface of 280 m^2/kg and a fineness of 82% passing a 200 mesh (75 micron sieve), whereas marketed cement exhibit a 340 m^2/kg of specific surface and a 98% passing 200 mesh, on average, in Canada.

As a matter of fact, cement ground in conventional ball mill systems generates a very high proportion of too fine particles (flour). These particles lower than 4-5 microns in size do not contribute to cement resistance properties on a long term. It is claimed that, by their high water demand during concrete making, their presence can even lower the compressive strength.

The proportion of flour in finished product averages 15% in weight. However, a gross calculation shows that this 15% fraction accounts for upto 80% of the specific surface of the cement. The problem lies in the grinding process.

Clinker Grinding (Table 7 and Figure 43) (cont'd)

It has been seen that because of the "intrinsic" long retention time in ball mills, the product at mill discharge contains a large amount of very fine particles which are not separated in the downstream classification stage. As mentioned in previous chapters, approximately 70% of readily sized material entering the separator is sent back to the mill with tailings for further grinding pass.

To avoid (at least partly) this situation, the mill system is run at high, even very high circulating loads. In some cases, the circulating load reaches 1000%. In case of short single compartment mills where the length to diameter ratio does not usually exceed 1.5, a porous (permeable) ball load facilitates the reduction of the retention time, whereas, in long mills ($L/D \geqslant 3$), grinding aids are inevitably needed. The benefit of high circulating load is that they permit the separator to cream off, in several passes, the material.

As mentioned in previous chapters, air separators are low efficiency machines, and a better classification does not seem possible in a one stage classification. Some trials are being made by various cement plants on a multistage classification. The results are encouraging. Hukki [15] reports that using his separators in series, the best balance mill classification corresponds to circulating load varying between 100 and 300% (Figure 44).

As in the case of raw mills, the best prospects for future developments to achieve substantial savings in cement grinding energy consumption will probably lie in the application of roll mills.

However, it seems that no such system has yet been adopted in the industry mainly due to the abrasiveness of clinker. It is hoped that this question will soon be revolved. It should not be forgotten that

COMMINUTION EQUIPMENT IN CEMENT PLANT (cont'd)

Clinker Grinding (Table 7 and Figure 43) (cont'd)

a sharp particle size distribution curve of the finished product will allow a reduction of 20-50 m^2/kg in specific surface.[26] This corresponds to approximately 5 kWh/t savings for at least the same quality of cement. Figure 45-1 shows that the particle size distribution of a product ground in a roller mill is much steeper than that of a product ground in a conventional ball mill. Figure 45-2 shows that a cement ground in a roller mill gives better compressive strengths in 28 days than that of a cement ground to the same Blaine fineness in a ball mill.

OPTIMIZATION

Proper control of the grinding process in the cement industry greatly affects the economics of the installation.

Raw Mix Grinding - Drying

In cement manufacturing for a given feed characteristic and equipment, the quality of the finished product is directly dependent upon the value of circulating load and therefore, the feed devices should be automated and optimum circulation load established.

In order to control the drying operation in the separator, the temperature of the exit gases is regulated by the amount of heat supplied to the separator. The optimization of the separator may be achieved by initiating control from a control room.

These automation devices may result in energy savings of 5 - 10%. However, great emphasis should be placed on the selection of the grinding machinery itself. Ball mills do not give good performance and they are already being replaced by roller mills. This may result in 20 - 30% savings in specific power consumption.

Cement Grinding

The problem lies in the grinding circuit equipment and their arrangements. The conventional tandem ball mill air separator does not give satisfactory results in terms of kWh/t and of particle size distribution of the product. The trend points to multi-stage classification and/or to the gradual substitution of ball mills by roller mill types. Figure 46 illustrates the flow sheet of a conventional grinding facility with one classification stage with a possibility of arranging two separators in series.

OPTIMIZATION (Cont'd)

Mill Feed Size

In case where the installation for dry raw grinding already comprises a ball mill, a small feed size, say 1 cm, will increase the mill products, hence improve the final kWh/t. and the only modification should be in the crushing installation.

A new crushing/grinding facility, to be designed, would include an impact crusher to reduce the size of quarried product of 1 m^3 size down to approximately 7 - 8 cm (3") followed by Roller mill. Since the feed size and the feed size continuity can be easily controlled by roller mill, it is not necessary to provide a closed circuit for the crushing operation.

The roller mill has not been adopted for cement grinding therefore, the best equipment seems to be a double rotator mill type where the tailings of the separator are not mixed with the fresh feed in the first compartment. Hence, ball load gradation is more suitalbe to the material being ground separately in both compartments.

OPTIMIZATION (cont'd)

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The Roller mill has not been adopted for cement grinding therefore, the best equipment seems to be a double rotator mill type where the tailings of the separator are not mixed with the fresh feed in the first compartment. Hence, ball load gradation is more suitable to the material being ground separately in both compartments.

CONCLUSION

In order to save energy from comminution in cement making, the plant should be custom designed according to the mechanical characteristics of the raw materials.

Equipment not too sensitive to abrasiveness should be selected. The machinery must relate to the material size at the different comminution stages to make optimum use of the equipment. The mill and separator should be carefully adjusted to yield a high percentage of particles of the diviser within the active size distribution fraction which imparts to the cement its maximum strength properties.

Mill overheating should be avoided. Ball should be designed to suit the charge and should be checked periodically to obtain a maximum comminution efficiency to avoid coating through heating. A good mill ventilation contributes greatly to mill efficiency.

Because a large fraction of too fine particles are created both in raw and cement grinding, the solution is to use a more efficient separator than the present ones available on the market. In the meantime, a multi-stage separation system offers better performance both in terms of kWh/t and of active size distribution fraction.

TABLE 1

PRODUCTION OF INDUSTRIAL MINERALS IN CANADA

	TONNES, 10^3	DOLLARS, 10^3
ASBESTOS	1,493	607,461
BARITE	x	1,953
GYPSUM	8,098	41,126
MAGNESITIC DOLOMITE, BRUCITE	x	8,990
NEPHELINE SYENITE	606	15,180
PEAT	480	41,150
POTASH (K_2O)	7,074	735,246
PYRITE, PYRRHOTITE	31	275
QUARTZ	2,368	26,579
SALT	6,881	109,848
SOAPSTONE, TALC PROPHYLLITE	90	3,439
SODIUM SULPHATE	443	25,211
SULPHUR IN SMELTER GAS	667	14,515
SULPHUR, ELEMENTAL	6,314	159,642
TITANIUM DIOXIDE, ETC.	x	75,670
COAL	33,200	860,000
CLAY PRODUCTS	-	121,526
CEMENT	11,765	653,877
LIME	1,859	82,774
STONE	109,719	330,708
SAND AND GRAVEL	285,221	457,120

x Not available

TABLE 2

RECENT UPDATE OF
AVERAGE IMPACT WORK INDICES

Material	Average	Range
Basalt	20.2	9.9-34.8
Bauxite	5.3	2.5-12.2
Calcite	8.2	5.8-12.2
Cement Clinker	4.2	1.4- 8.8
Cement Raw Material	11.7	3.6-27.4
Clay	4.8	3.7- 6.1
Dolomite	12.8	5.4-31.4
Granite	15.7	6.7-38.0
Gravel	16.7	6.9-26.8
Gypsum Rock	6.9	4.3-11.7
Limestone	11.1	3.3-27.6
Phosphate Rock	3.3	0.5-11.7
Quartzite	12.9	5.2-19.1
Sandstone	13.1	6.5-28.6
Schist	12.5	4.1-23.5
Shale	10.6	5.8-19.0
Silica Rock	9.4	4.2-15.9
Slag	12.8	1.3-21.9
Stone	16.9	10.4-27.5

(After Allis-Chambers, 1977)

TABLE 3

RECENT UPDATE OF
AVERAGE ABRASION INDICES

Material	Average	Range
Basalt	.45	.19 - .83
Bauxite	.02	.003- .12
Cement Clinker	.08	.009- .17
Cement raw mix	.05	.001- .83
Clay, Calcined	.04	.004- .07
Dolomite	.03	.01 - .07
Feldspar	.19	.07 - .30
Granite	.40	.10 - .78
Gravel	.29	.11 - .43
Limestone	.05	.00 - .65
Magnesite	.08	.04 - .10
Marble	.01	.002- .04
Phosphate Rock	.02	.01 - .02
Quartize	.69	.19 - .99
Schist	.12	.11 - .13
Shale	.004	.003- .005
Silica Rock	.29	.06 - .83
Slag	.28	.01 - .52
Slate	.003	.003- .003
Stone	.22	.07 - .32

(After Allis-Chambers, 1977)

TABLE 4

CRUSHING MACHINERY COMPARISON

CRUSHER TYPE	FEED IN	PRODUCT OUT	PHYSICAL CHARACTERISTICS OF FEED MATERIAL				MAIN APPLICATION FIELDS
			HARDNESS	ABRASIVENESS	MOISTURE	RED.RATIO	
JAW CRUSHER	~ 4'	~ 1"	hard to very hard	Low to high	Dry or Slightly Sticky	3 to 10:1	All materials except when soft & sticky - slag
GYRATORY	~ 4'	~ 1"	medium to very hard	High	Dry or Slightly moist-not sticky	6 to 8:1	All materials except when soft sticky & very hard
CONE	~ ½'	~ ½"	medium hard to hard	High	Dry or slightly sticky	6 to 8:1	All materials except when soft sticky and very hard
SINGLE ROLL DOUBLE ROLL	~ 4' ~ ¼'	~ 8" ~ ½"	soft - slightly hard	Low	Dry,moist - very sticky if teethed rolls	4 to 6:1	Coal, limestone, clay, gypsum phosphates, potash
IMPACTOR	~ 5'	~ 1"	soft to medium hard	Low	Moist to slightly sticky	15 to 31:1	Ceramics, lime-stone, cement raw fertilizers, coal, gypsum
HAMMERMILL	~ 4"	~3/4"	soft to medium hard	Low	Dry to slightly moist	10 to 30:1	Limestone, coal phosphates Barite, cement raw, potash

TABLE 5

RAW GRINDING

Comparison of Typical Energy Requirements of Various Milling System, Grinding to Approximately 12%, - 90 microns (Medium Limestone).

	Tertiary Crushing	Mill only	Fan + Ancillaries	Total
	Kwh/t			
Air swept ball mill	0.40	16.0	4.4	20.7
Double rotator ball mill	0.40	12.8	5.3	18.5
Short single chamber	0.40	12.8	5.0	18.2
Roller mill	-	7.6	7.1	14.7

(After Rock products)

TABLE 6

ROLLER MILL POWER DEMAND IS COMPARED TO CONVENTIONAL DRY-GRINDING BALL MILL REQUIREMENTS

Sample	Work Index Grindability at Mesh		Kwh/ton			Roller Mill Test	Energy-Conscious Roller Mill Operation Kwh/ton				Capital-Conscious Roller Mill Operation Kwh/ton			
	14	200	Crushing	Ball Mill	Circuit Total		Mill	Fan	Circuit Total	% of Ball Total	Mill	Fan	Circuit Total	% of Ball Total
A	13.6	11.8	0.4	16.8	19.3	9.3	7.8	5.3	13.5	70	8.1	7.5	16.0	83
B	12.4	7.0	0.4	9.6	12.1	6.4	5.2	3.1	8.7	74	5.4	4.3	10.1	84
C	11.3	8.0	0.3	11.0	13.4	6.5	5.3	3.6	9.3	69	5.6	5.2	11.2	84
D	11.1	7.0	0.3	9.7	12.1	5.7	4.7	2.9	8.0	66	4.9	4.0	9.3	77
E	8.3	4.9	0.3	6.7	9.1	5.2	4.2	2.6	7.2	79	4.4	3.5	8.3	91
F	16.8	12.0	0.5	17.2	19.8	10.7	8.8	5.2	14.4	73	9.0	6.7	16.1	81
G-1	17.5	9.6	0.5	13.3	15.9	9.6	7.9	4.5	12.8	81	8.1	6.2	14.7	93
G-2	16.7	10.2	0.5	14.3	16.9	9.6	7.9	4.5	12.8	76	8.1	6.2	14.7	87
H	10.9	8.4	0.3	11.5	13.9	7.4	6.2	4.2	10.8	78	6.5	6.3	13.2	95
I-1	10.6	5.4	0.3	7.4	9.8	4.3	3.5	2.8	6.7	68	3.6	4.0	8.0	82
I-2	8.1	6.5	0.3	8.9	11.3	4.8	3.9	3.0	7.3	65	4.1	3.9	8.4	74
J	16.5	9.6	0.5	13.3	15.9	8.6	7.1	4.3	11.8	74	7.4	5.8	13.6	86
K	10.9	10.1	0.3	14.1	16.5	8.0	6.6	4.0	11.4	69	6.9	5.9	13.2	80
L	13.5	9.0	0.4	12.5	15.0	8.9	7.3	4.8	12.5	83	7.6	6.7	14.7	98
M	8.0	8.5	0.3	11.7	14.1	6.6	5.4	4.2	10.0	71	5.6	5.6	11.6	83
N	14.4	11.2	0.4	16.0	18.5	9.9	8.1	4.5	13.0	70	8.4	6.2	15.0	81
O-1	10.2	12.0	0.3	17.1	19.5	7.5	6.3	4.7	11.4	58	6.6	7.0	14.0	72
O-2	10.7	11.7	0.3	16.7	19.1	6.5	5.3	3.8	9.5	50	5.6	5.4	11.4	60
P	8.1	8.9	0.3	12.3	14.7	5.9	4.8	3.1	8.3	57	5.0	4.3	9.7	66
Q	12.5	9.4	0.4	13.1	15.6	7.5	6.2	4.1	10.7	69	6.5	6.0	12.9	83
R	14.1	11.0	0.4	15.5	18.0	10.0	8.3	5.5	14.2	79	8.6	7.4	16.4	91
S	11.0	8.2	0.3	11.3	13.7	6.4	5.2	3.1	8.7	64	5.4	4.4	10.2	75
Avg.										70				82
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

TABLE 7

FINISH GRINDING

Normal Cement

Fineness	Kwh/t	Extra Kwh/tonne above target	3000 HP Mill output tonne/h	Loss in output tonne/h
Target	34.1		65.5	
If grind to 100 cm^2/g above target	35.6	1.5	62.7	2.8
200 cm^2/g above target	37.0	3.0	60.1	5.3
300 cm^2/g above target	39.0	5.0	57.2	8.3

(After Rock product)

TABLE 8

CONCRETE AGGREGATE

C.S.A. STANDARD A23.1

Fine aggregate shall consist of natural sand, manufactured sand, or an approved combination hereof.

GRADING LIMITS FOR FINE AGGREGATE

Sieve Size	Total Passing Sieve Percentage by Weight	
	Normal Weight	Lightweight
3/4 inch (9.5 mm)	100	100
No. 4 (4.75 mm)	95-100	85-100
No. 8 (2.36 mm)	80-100	
No. 16 (1.18 mm)	50-85	40-80
No. 30 (600 m)	25-60	
No. 50 (300 m)	10-30	10-35
No. 100 (150 m)	2-10	5-25

TABLE 9
CONCRETE AGGREGATE

C.S.A. STANDARD A23.1

Coarse aggregate shall consist of crushed stone, gravel, air cooled iron blast furnace slag, lightweight aggregate, or a combination thereof, conforming to the requirements of the Standard

GRADING REQUIREMENTS FOR COARSE AGGREGATE

Group	Nominal Size Of Aggregate		Total Passing Each Sieve / Per Cent By Weight												
			4 in. (100 mm)	3½ in. (90 mm)	3 in. (75.0 mm)	2½ in. (63 mm)	2 in. (50.0 mm)	1½ in. (37.5 mm)	1 in. (25.0 mm)	¾ in. (19.0 mm)	½ in. (12.5 mm)	3/8 in. (9.5 mm)	No.4 (4.75 mm)	No.8 (2.36 mm)	No.16 (1.18 mm)
GROUP I	1½ in. to No. 4	37.5 to 4.75 mm	-	-	-	-	100	95 to 100	-	35 to 70	-	10 to 30	0 to 5	-	-
	1 in. to No. 4	25.0 to 4.75 mm	-	-	-	-	-	100	95 to 100	-	25 to 60	-	0 to 10	0 to 5	-
	¾ inc. to No. 4	4.75 mm to 4.75 mm	-	-	-	-	-	-	100	90 to 100	30 to 75	20 to 55	0 to 10	0 to 5	-
	½ in. to No. 4	12.5 to 4.75 mm	-	-	-	-	-	-	-	100	90 to 100	40 to 70	0 to 15	0 to 5	-
	3/8 in. to No. 8	9.5 to 2.36 mm	-	-	-	-	-	-	-	-	100	85 to 100	10 to 30	0 to 10	0 to 5
GROUP II	3½ to 1½ in.	90 to 37.5 mm	100	90 to 100	-	25 to 60	-	0 to 15	-	0 to 5	-	-	-	-	-
	2½ to 1½ in.	63 to 37.5 mm	-	-	100	90 to 100	35 to 70	0 to 15	-	0 to 5	-	-	-	-	-
	2 to 1 in.	50 to 25.0 mm	-	-	-	100	90 to 100	35 to 70	0 to 15	-	0 to 5	-	-	-	-
	1½ in. to ¾ in.	37.5 to 19.0 mm	-	-	-	-	100	90 to 100	20 to 55	0 to 15	-	0 to 5	-	-	-
	¾ in. to 3/8 in.	19.0 to 9.5 mm	-	-	-	-	-	-	100	85 to 100	-	0 to 20	0 to 5	-	-
	½ in to 3/8 in.	12.5 to 9.5 mm	-	-	-	-	-	-	-	100	85 to 100	0 to 45	0 to 10	-	-
	3/8 to No. 4	9.5 to 4.75 mm	-	-	-	-	-	-	-	-	100	85 to 100	0 to 20	0 to 5	-

Note: Group I comprises aggregate gradings most commonly used in concrete production. Group II provides for gape-grading, pumping, etc.

TABLE 10 -A

MAIN RELATED INDUSTRIES/USES

INDUSTRIAL ROCKS	PROPERTIES G	Wi	A	REDUCTION TYPES	USES - INDUSTRIES
GRANITE	2.68	14.4	.39	C	Aggregate in concrete Dimension stone: monuments, buildings, paving blocs
BASALT-DIABASE	2.89	20.4	-	C	Aggregate (high density) in concrete and road metal (75%)
PUMICE-PUMICITE	1.96	11.9	.12	B-C	Abrasive - Cement manufacturing (pozzolan)-(light) aggregate
PERLITE	-	-	.05	B-C	Aggregate in plaster and wall board (70%) Aggregate in lightweight concrete (15%)
SLATE	2.48	13.8	.14	B-C	Dimension form - expanded slate to light aggregate
MARBLE	-	-	-	C	Building - statuary - crushed marble - same uses as limestone
SAND-GRAVEL S.	2.65	16.5	-	B-C	Aggregate in mortar and concrete construction and paving industries Small tonnage of sand in glass industries
G.	-	19	.31		
SANDSTONE	2.68	11.5	-	B-C	Dimension stone. If well cemented, sandstone may be used as aggregate. If weakly cemented, used as molding sand, glass sand.
CLAY	2.23	7.1	-	B	Ceramics: highgrade ceramics, structural clay products - cement manufacturing - lightweight aggregate Refractories filler and in paper industry - drilling muds - as adsorbent

Size Reduction Type
A - liberate valuable minerals
B - generate surface area for chemical reaction
C - to produce fragmented rocks or minerals of required size

Abrasiveness : A - when A increases, the material abrasiveness increases
Bond's work index : Wi- A high Wi means a material difficult to grind
Specific gravity : G

TABLE 10-B

MAIN RELATED INDUSTRIES/USES

INDUSTRIAL ROCKS	PROPERTIES G	Wi	A	REDUCTION TYPES	USES - INDUSTRIES
LIMESTONE	2.69	11.6	.03	B-C	Structural stone, cement manufacturing - aggregate - metallurgie (as a fluxstone in the milling process) - lime (construction and agriculture)
DOLOMITE	2.82	11.3	.02	B-C	Structural stone - aggregate - refractory industries - fluxing agent
PHOSPHATE	2.66	10.1	-	B	Fertilizer - Orthophosphoric acid (food, chemical, drugs)
GYPSUM	2.69	8.2	-	B	Plaster, prefabrication industries - cement manufacturing
SALT	-	-	-	-	Food industry - chemical industry - soap and dyes - processing of textiles and leather - ice control water treatment - metallurgy

TABLE 10-C

MAIN RELATED INDUSTRIES/USES

INDUSTRIAL MINERALS	PROPERTIES G	Wi	A	REDUCTION TYPE	USES - INDUSTRIES
NEPHELINE-SYENITE	-	-	-	A-B	Glass industry - ceramics,glases and enamels
FELDSPAR	2.59	11.7	-	A-B	Fluxing agent in ceramics - glass manufacturing
MICA	2.89	134.5	-	A-B	Electrical and Electronic applications Paints ingredient - lubricant
LITHIUM MINERALS	-	-	-	A-B	Glassmaking - ceramics - lubricant Nuclear, airospatial industries
BERYL	-	-	-	A-B	Hardening agent in alloys (90%)
QUARTZ CRYSTAL	2.64	12.8	.18	A	Jewelry - ratio circuits
FLUROSPAR	2.98	9.8	-	A-B	Fluxing agent - hydrofluoric acid for alumina industry, oil refinery, ceramics
BARITE	4.28	6.2	-	B	Heavy circulating fluid (drilling mud) in oil and gas drilling (95%)
MAGNESITE	5.22	16.8 10.2	.08 .25	B	Refractions (90%)
GRAPHITE	1.75	45.0	-	-	Metallurgical industry (foundry facings - crucibles) Steel making - lubricant
ASBESTOS	-	-	-	A	Spinning fibers = Asbestos thread, yarn, tape, cloth Non spinning fibers = compressed, molded or cast product; felted mass in a binder ex. Portland cements
TALC	-	-	-	B	Ceramics - paints - lubricant (paper industry)
VERMICULITE	-	-	-	B	Insulation - lightweight concrete - plaster mix

TABLE 10-D

MAIN RELATED INDUSTRIES/USES

INDUSTRIAL MINERALS	PROPERTIES G	Wi	A	REDUCTION TYPE	USES - INDUSTRIES
DIAMOND	-	-	-	A	Abrasive - Precision tool
POTASH MINERALS	2.37	8.9	-	B	Fertilizer (95%)
SODIUM MINERALS	2.10	13.0	-	B	Chemical - glass making - paper industry
BORATES	-	-	-	-	Glass making - ceramics
NITRATES	-	-	-	B	Fertilizers - explosive industries
SULFUR	-	11.5	.00	-	60% is consumed in the production of fertilizers Others = sulfuric acid production

FIG. 1 GRAPHICAL REPRESENTATION OF TWO DIFFERENT CEMENTS

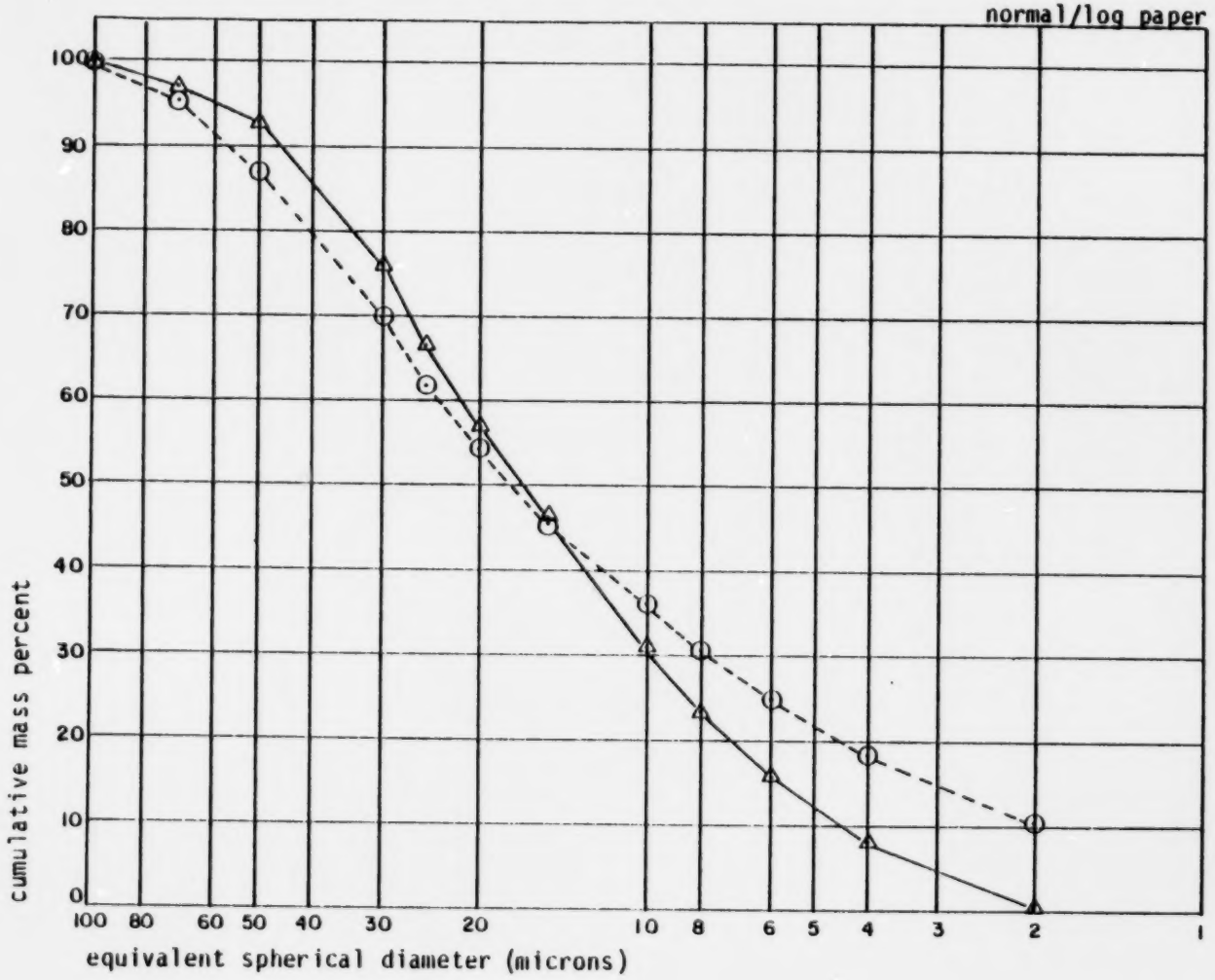


FIG. 2 GRAPHICAL REPRESENTATION OF TWO DIFFERENT CEMENTS

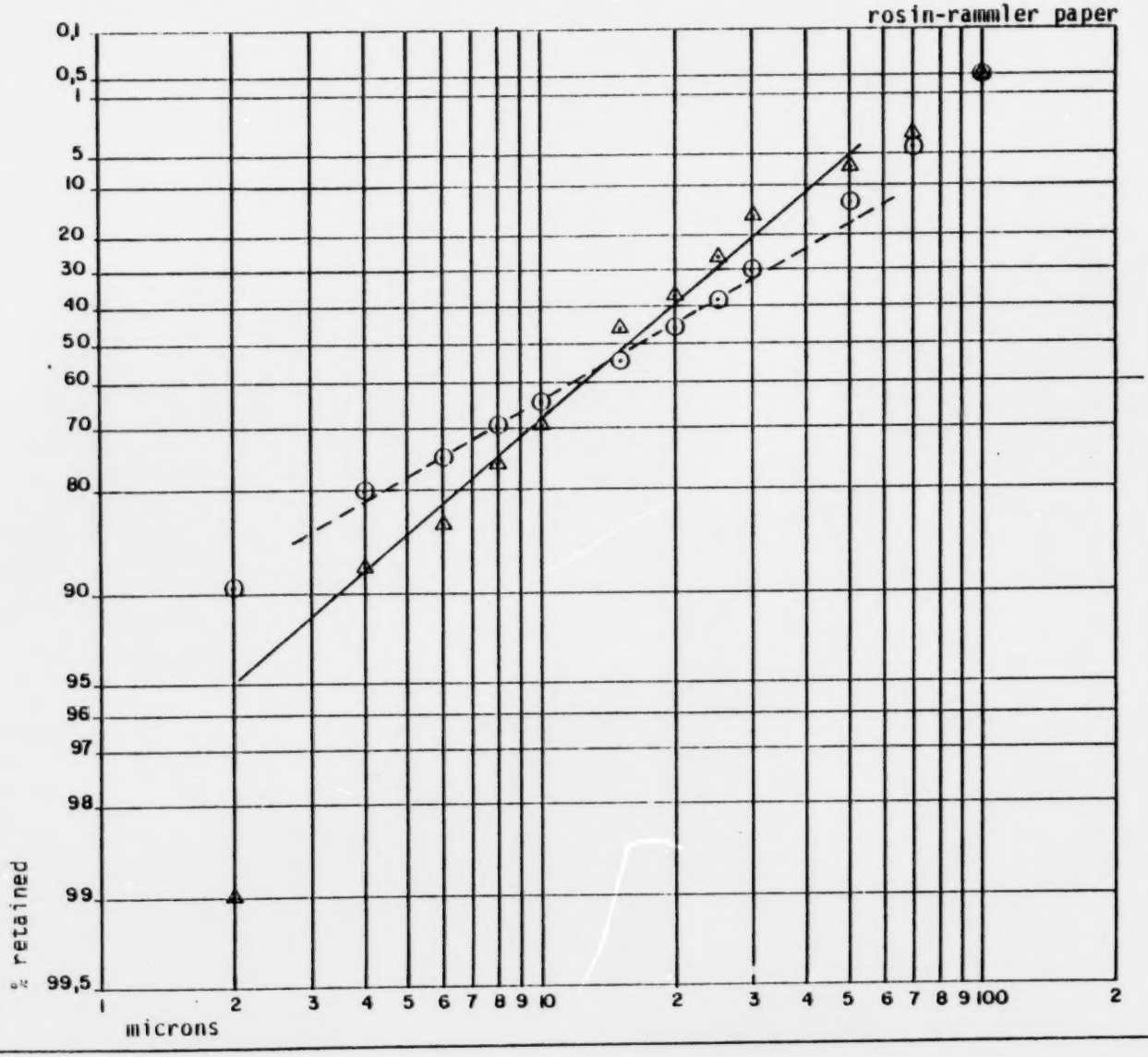
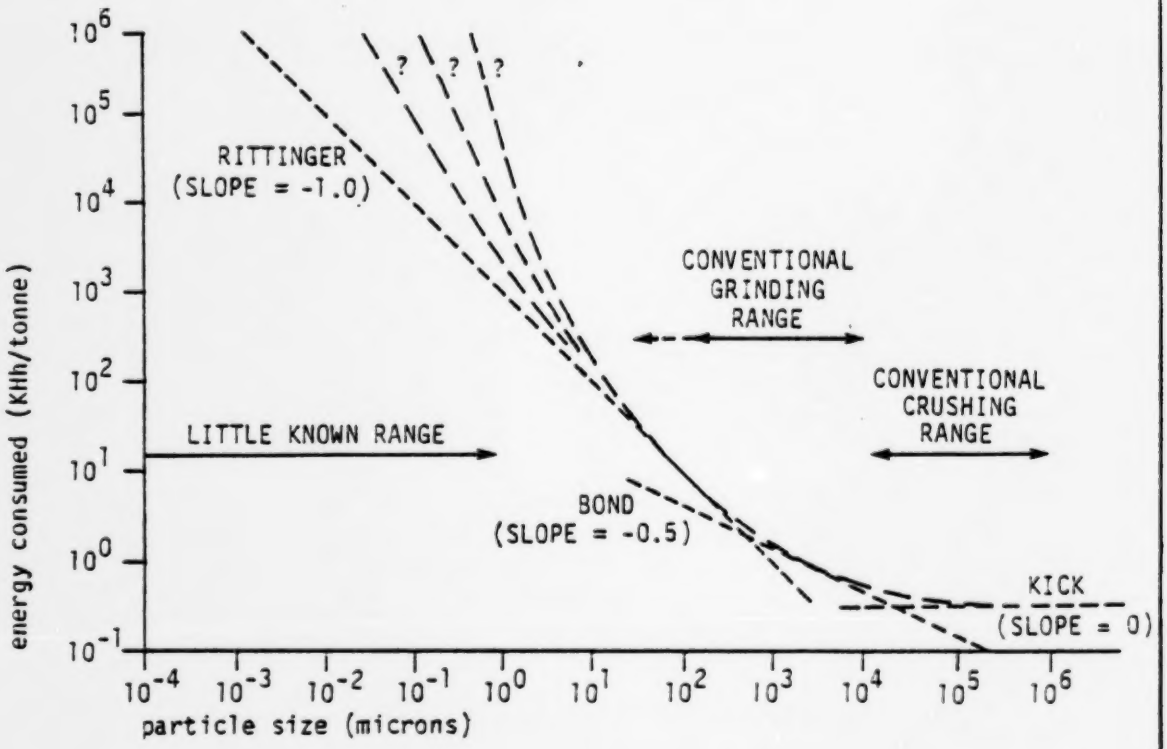


FIG. 3 RELATIONSHIP BETWEEN ENERGY INPUT AND PARTICLE SIZE
(AFTER HUKKI 1961)

KICK'S FORMULA: 10 mm < D < 100 mm (CRUSHING AND COARSE GRINDING)

BOND'S FORMULA: 2,500 cm^2/g < D < 10 mm

RITTINGER'S FORMULA: D < 2,500 cm^2/g



LYNCH(18)

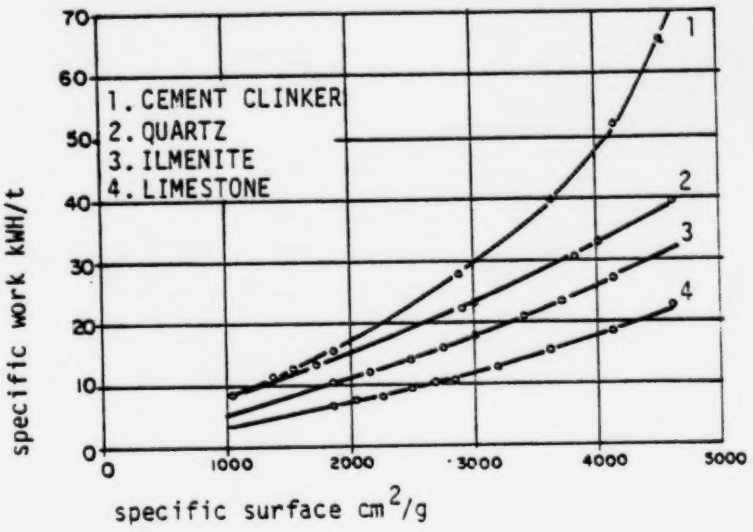


FIG. 4 GRINDABILITY CURVES OF FOUR DIFFERENT MATERIALS; SPECIFIC WORK AS A FUNCTION OF THE SPECIFIC SURFACE

ZISSELMAR(32)

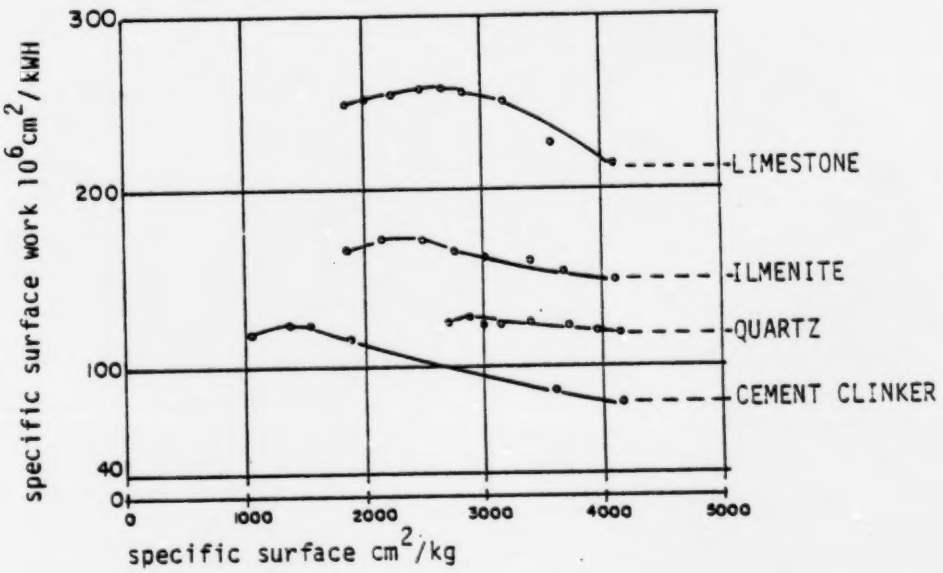


FIG. 5 GRINDABILITY CURVES OF FOUR DIFFERENT MATERIALS; GRINDABILITY AS A FUNCTION OF THE SPECIFIC SURFACE

ZISSELMAR(32)

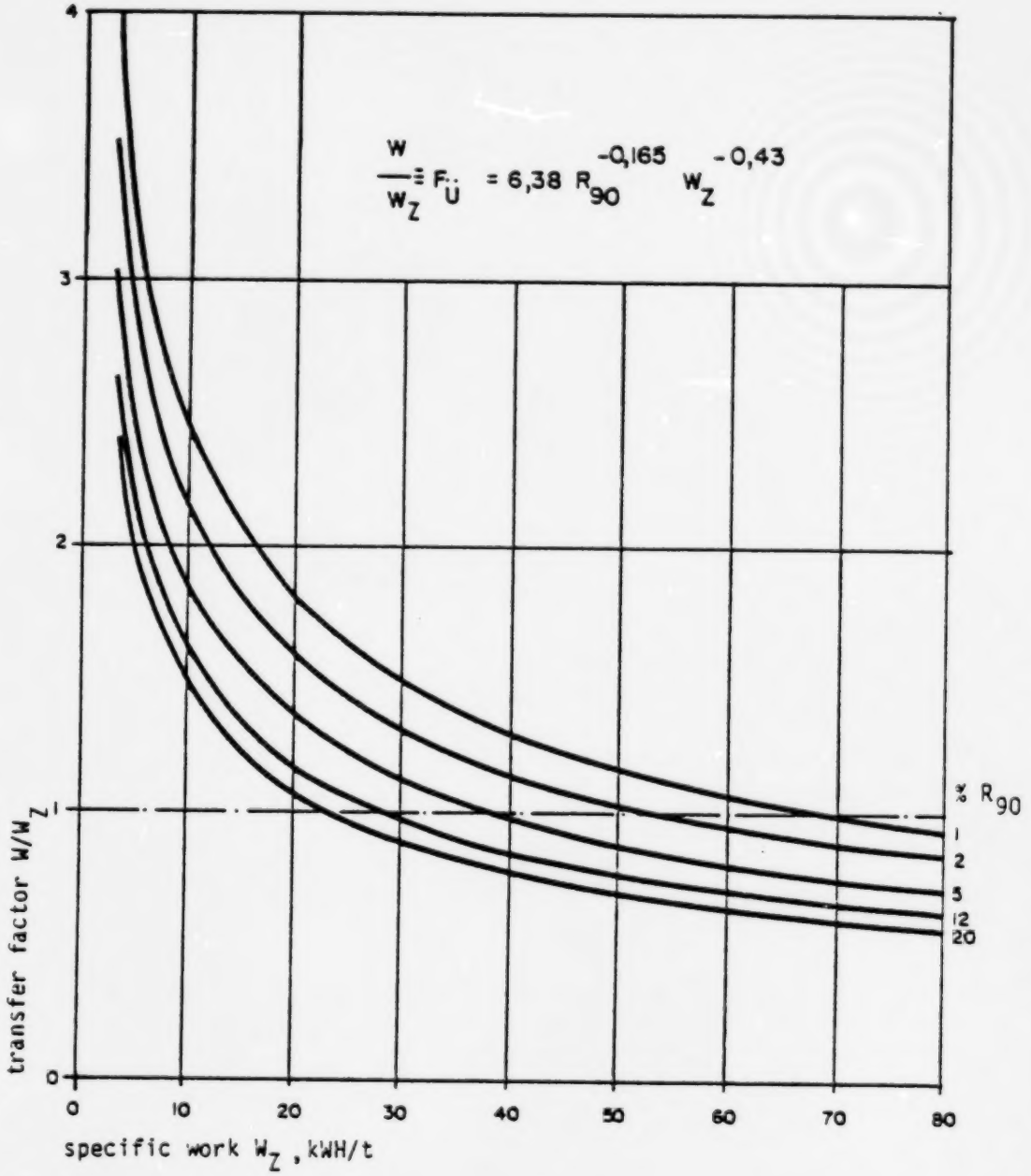


FIG. 6 TRANSFER FACTOR AS A FUNCTION OF THE SPECIFIC WORK MEASURED ON THE BASIS OF THE METHOD ACCORDING TO ZEISEL

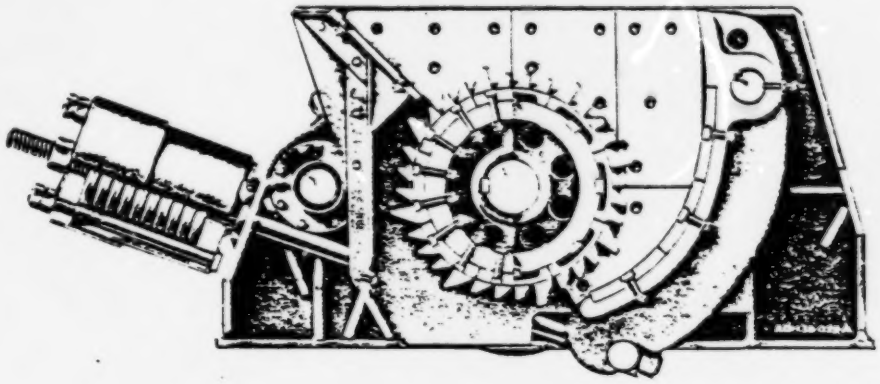


FIG. 7 SINGLE ROLL CRUSHER

DRAGON(6)

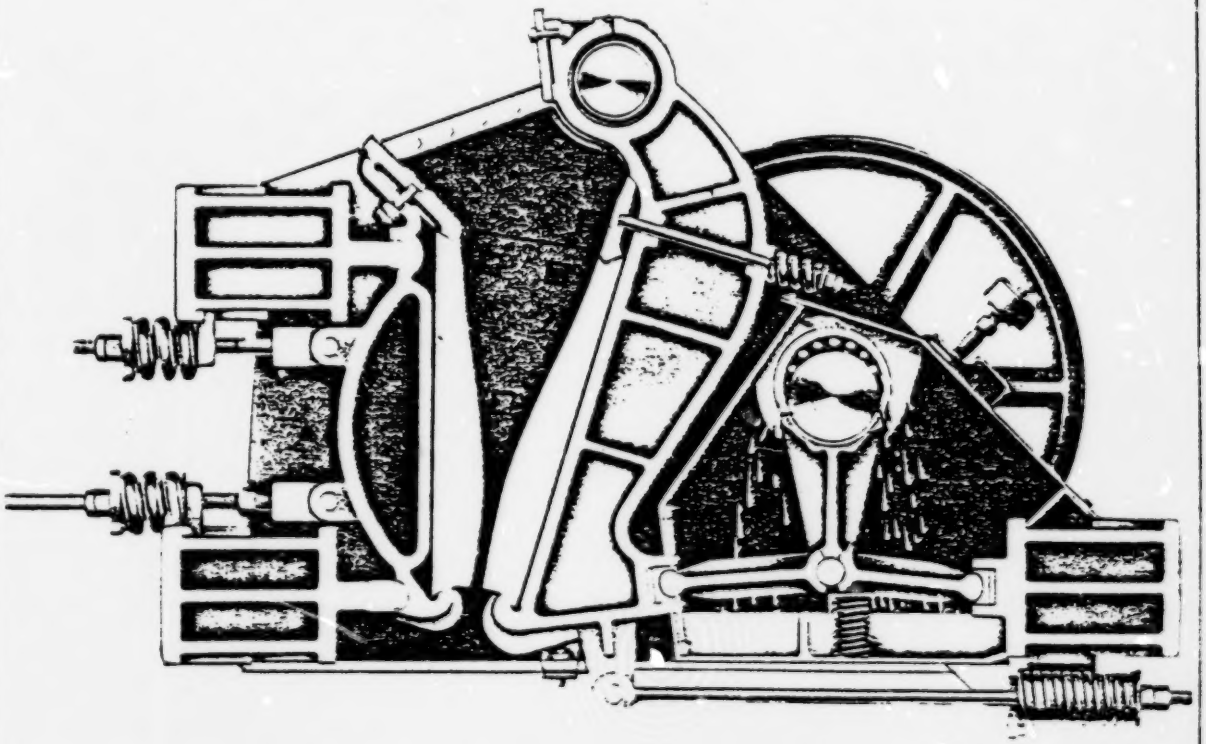


FIG. 8 JAW CRUSHER

PENNSYLVANIA(23)

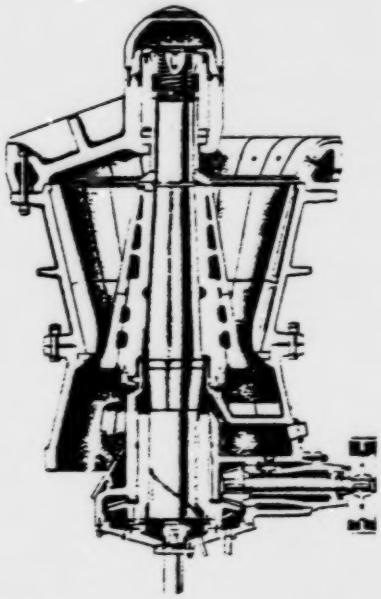


FIG. 9 GYRATORY CRUSHER

DRAGON(5)

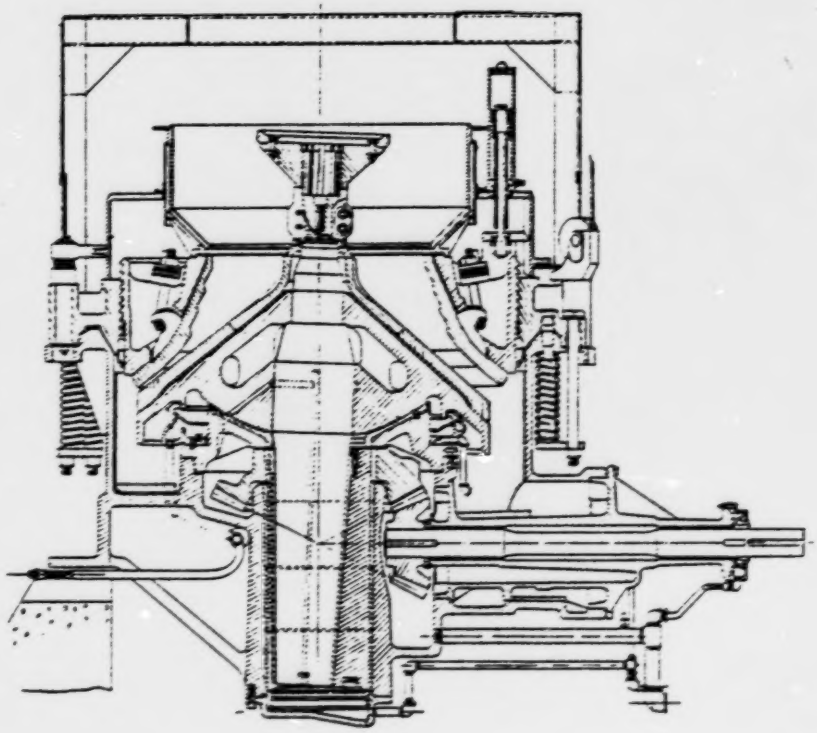


FIG. 10 CONE CRUSHER (NORDBERG)

BLANC(2)

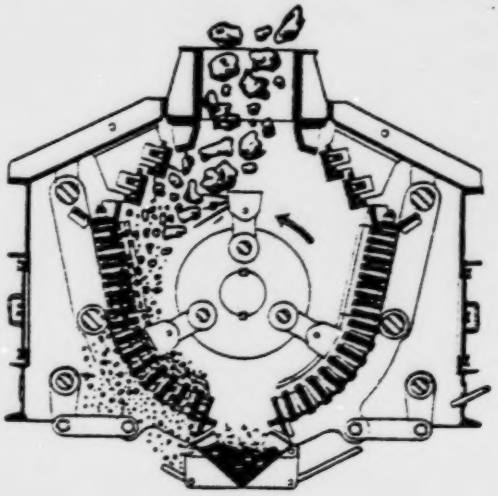


FIG. 11-1 REVERSIBLE HAMMERMILL FOR STONE ORES

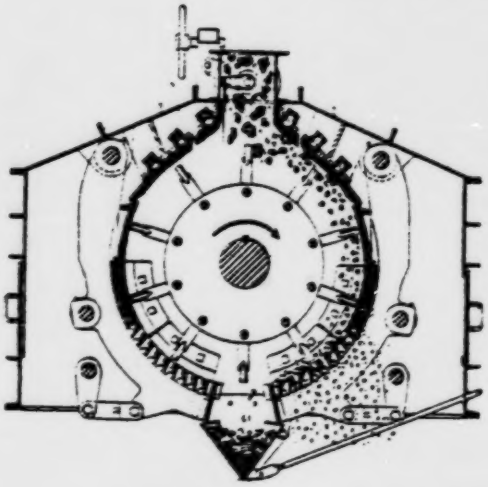


FIG. 11-2 REVERSIBLE HAMMERMILL FOR COAL

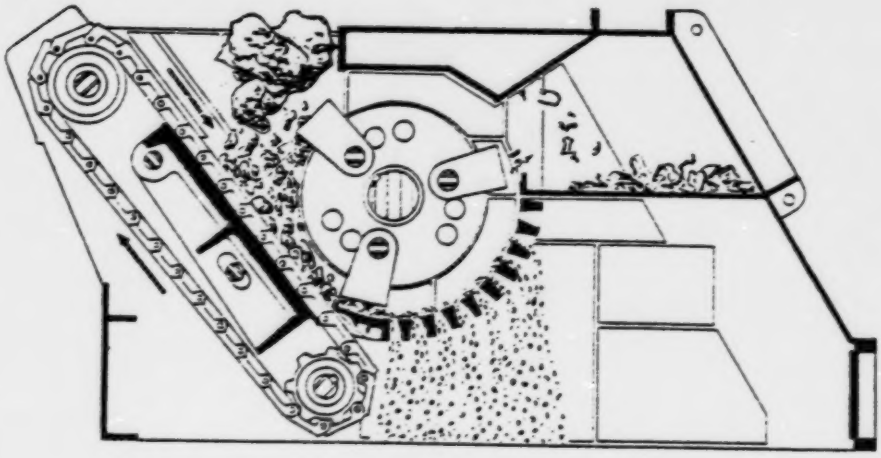


FIG. 11-3 NON CLOG HAMMERMILL

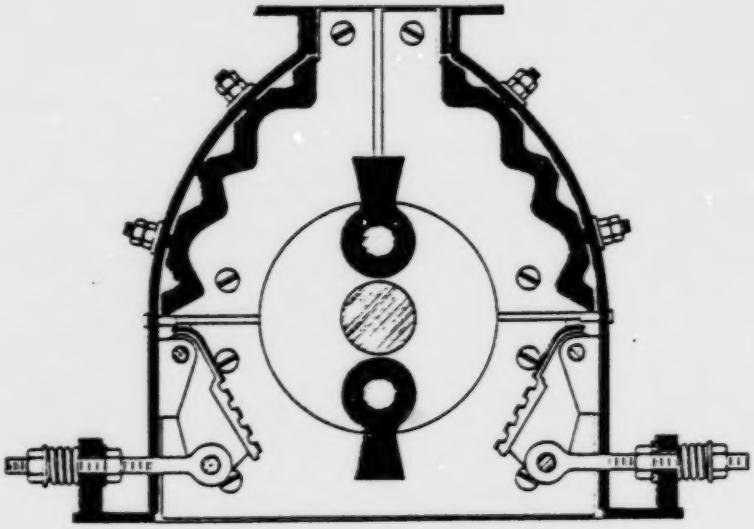


FIG. 12-1 SMALL REVERSIBLE IMPACTOR

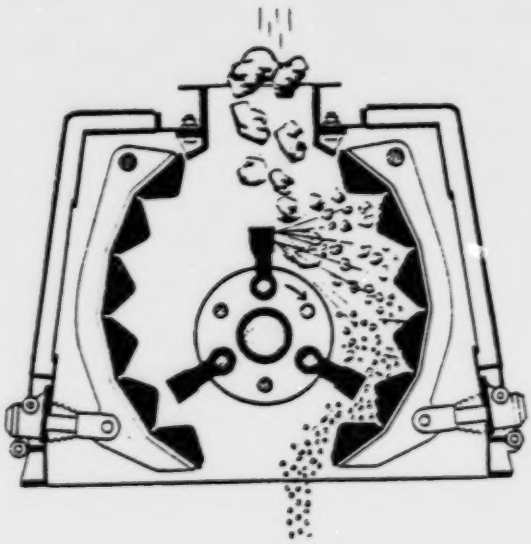


FIG. 12-2 REVERSIBLE IMPACTOR

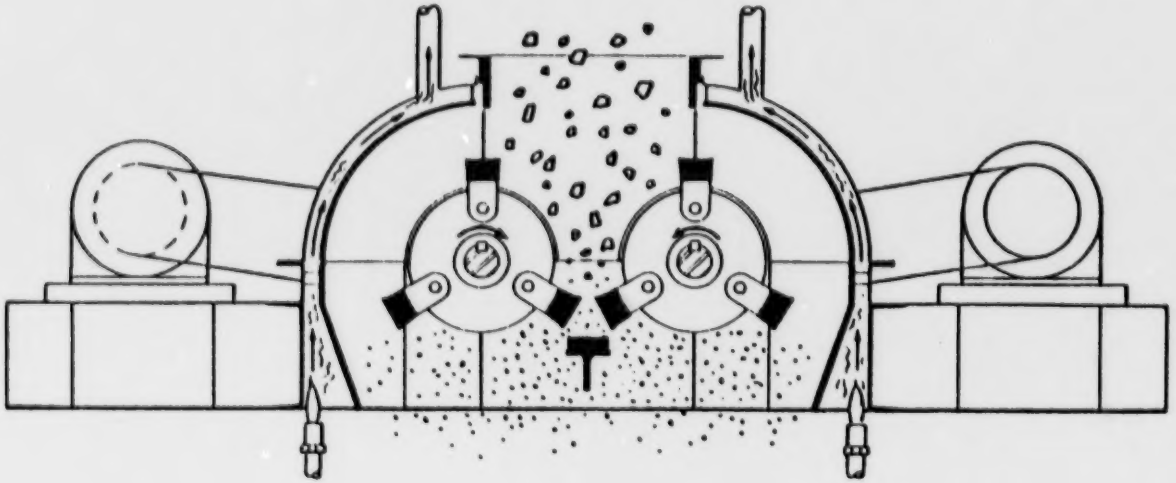


FIG. 12 -3 TWIN ROTOR IMPACTOR (FOR VERY STICKY MATERIAL)

PENNSYLVANIA(23)

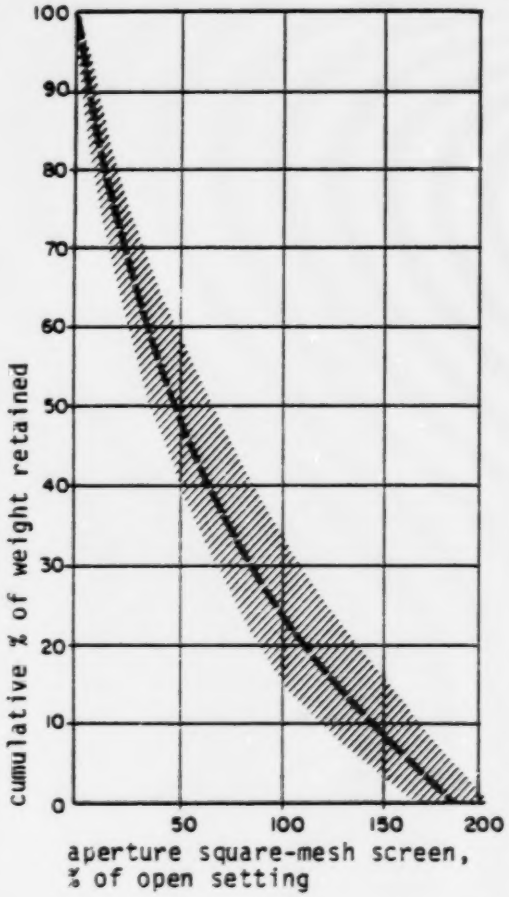


FIG. 13-1 SIZE DISTRIBUTION IN-JAW CRUSHER PRODUCT

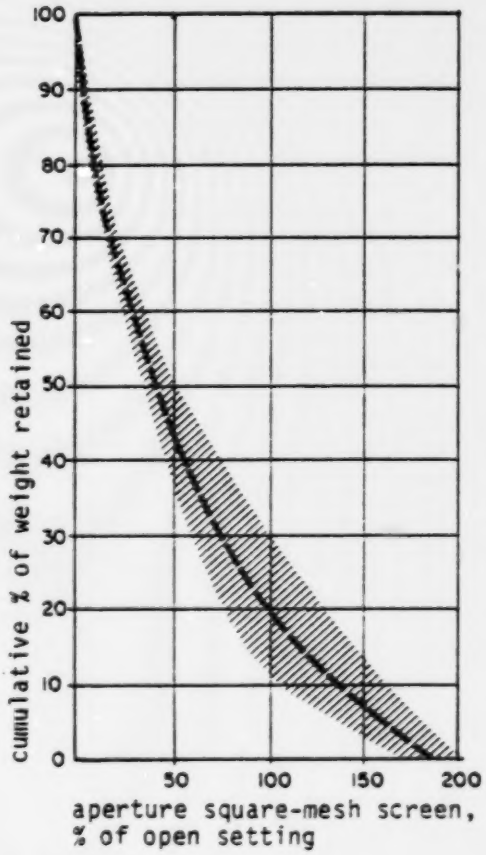


FIG. 13-2 SIZE DISTRIBUTION OF GYRATORY-CRUSHER PRODUCT

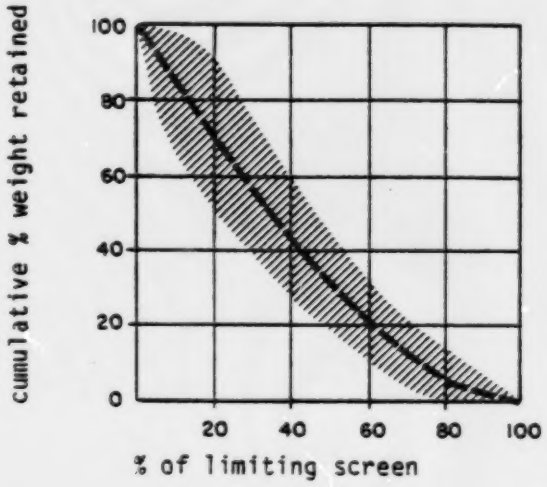
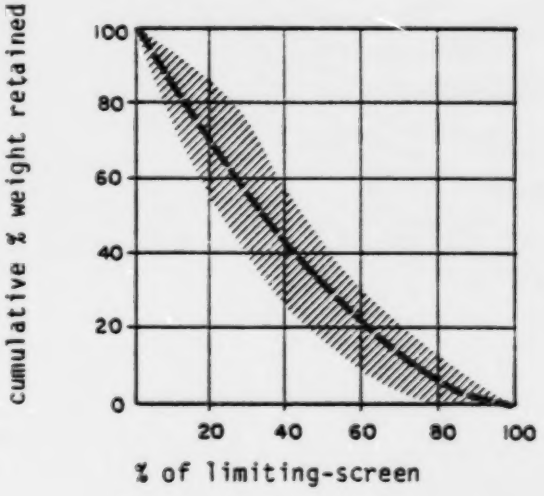


FIG. 13-3

SIZE OF PRODUCT OF STANDARD CONE CRUSHER



SIZE OF PRODUCT OF SHORT-HEAD CONE CRUSHER

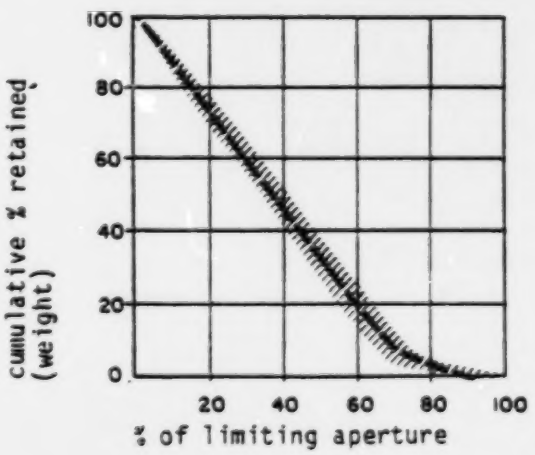
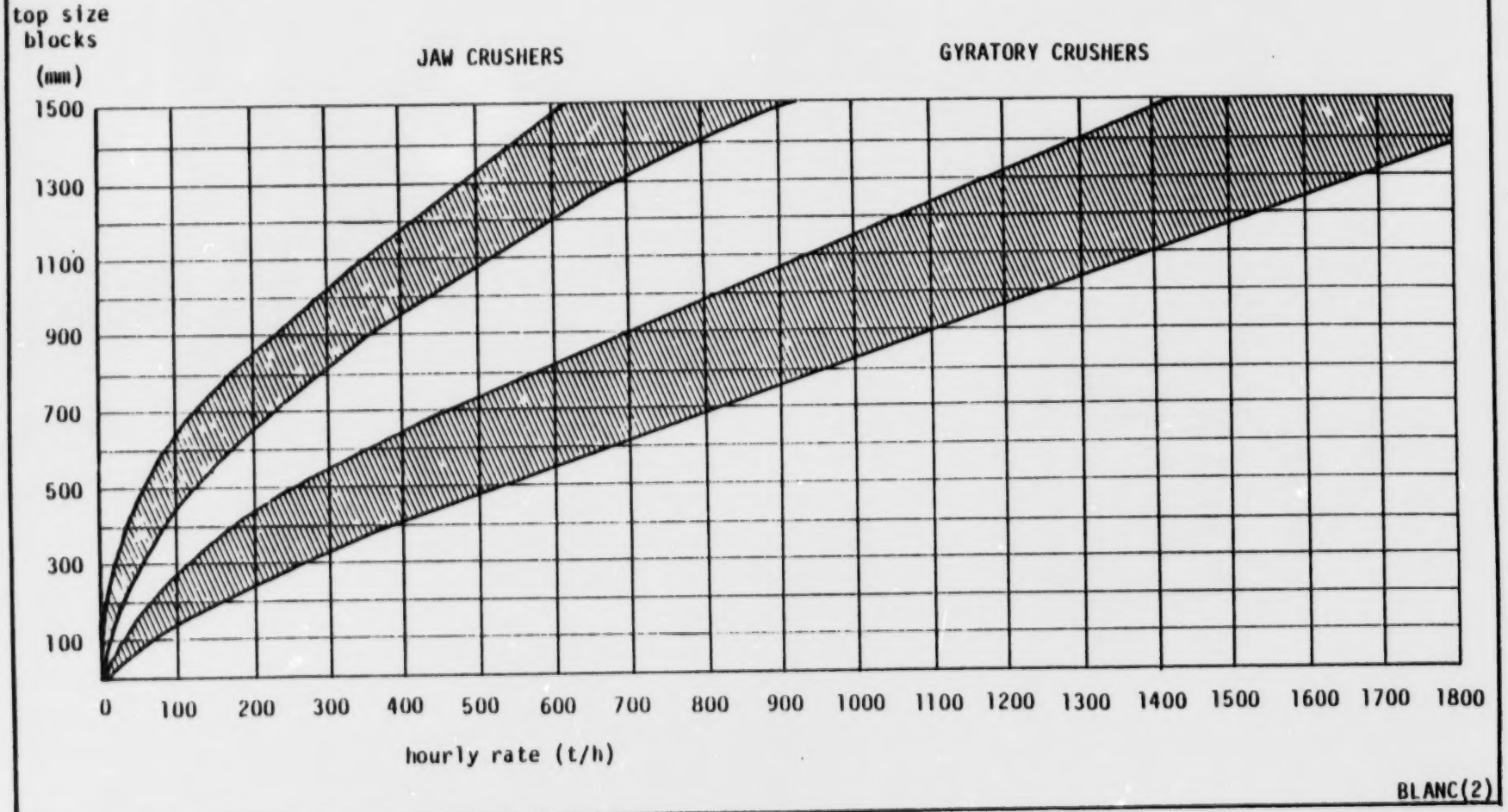


FIG. 13-4

CHARACTERISTIC PRODUCT OF SINGLE-ROLL CRUSHER

FIG. 14 JAW AND GYRATORY CRUSHERS COMPARISON



BLANC(2)

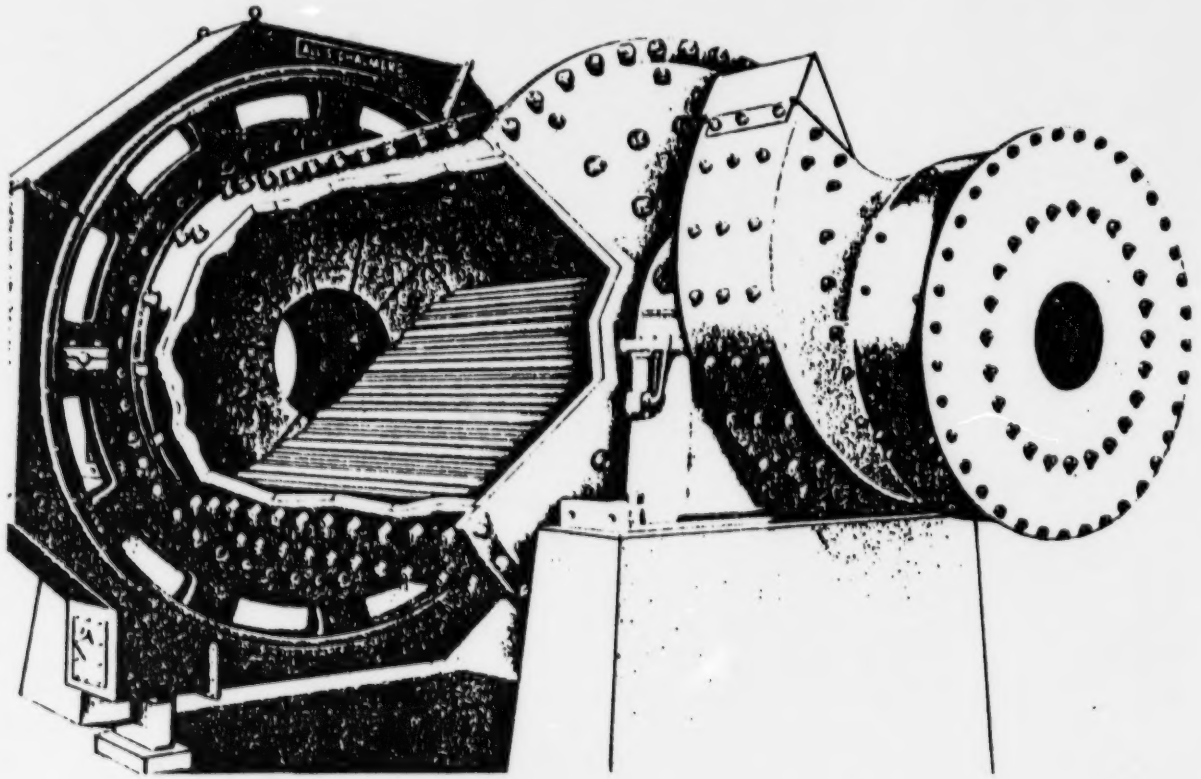


FIG. 15 OVERFLOW ROD MILL

ROWLAND & KJOS(25)

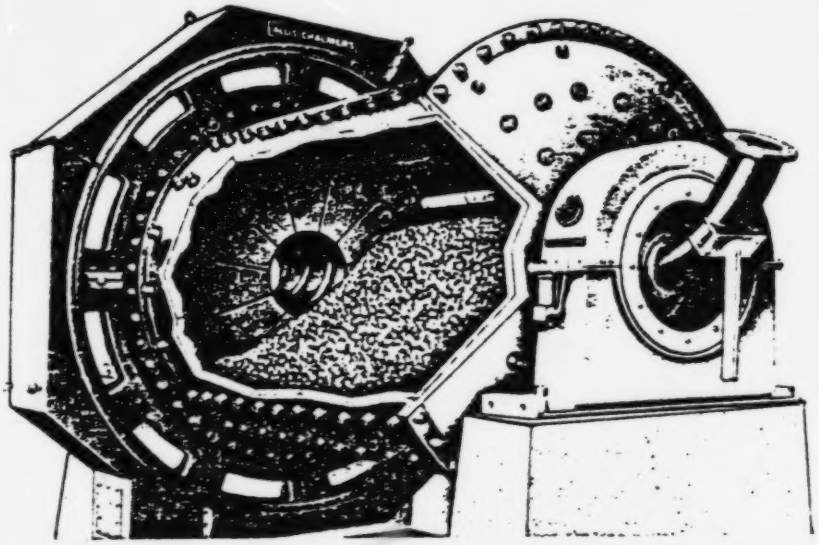


FIG. 16-1 OVERFLOW BALL MILL

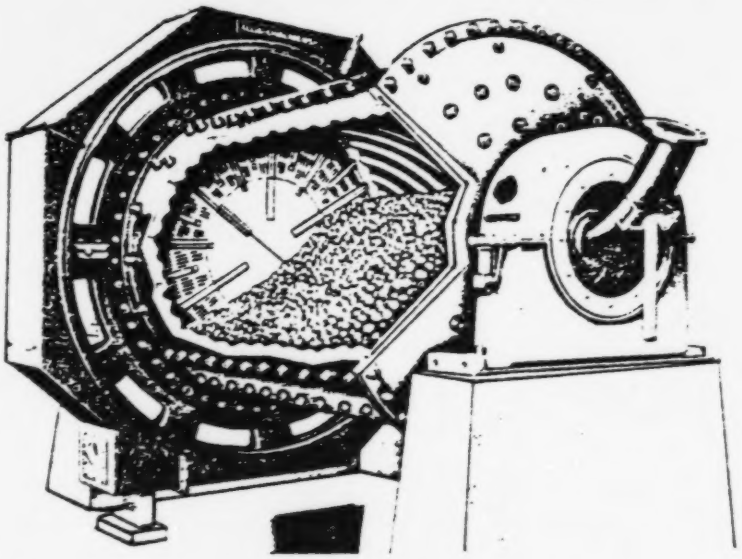


FIG. 16-2 DIAPHRAGM BALL MILL

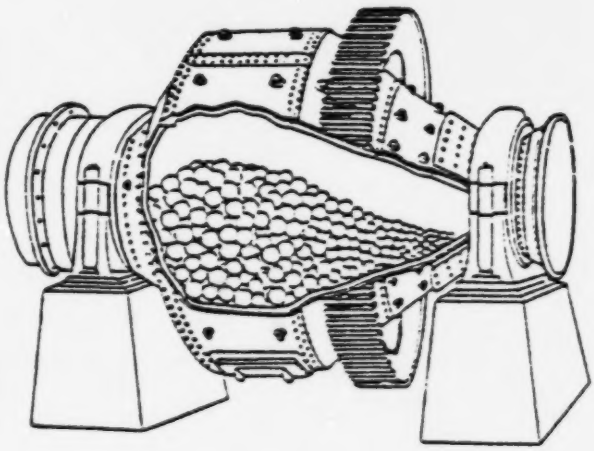
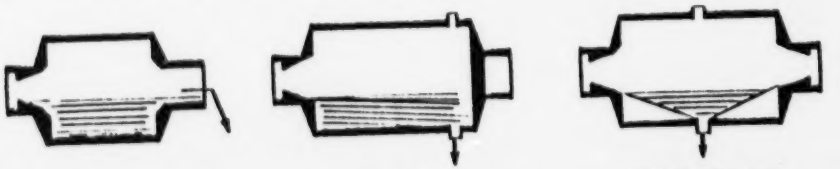


FIG. 17 CONICAL MILL

FIG. 18 ROD MILL DISCHARGE ARRANGEMENTS

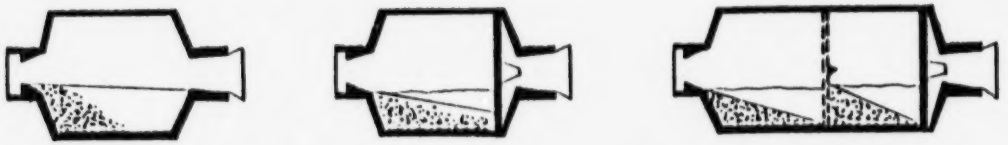


	OVERFLOW	END PERIPHERAL	CENTER PERIPHERAL
PROCESS	WET ONLY	WET OR DRY	WET OR DRY
MAX. REDUCTION RATIO	15 - 20 : 1	12 - 15 : 1	4 - 8 : 1
TYPICAL GRINDS	10-35 MESH	4-12 MESH	3 - 6 MESH
CAPACITY	NORMAL	NORMAL	DOUBLE
TYPICAL SPEED (% CRITICAL)	60 - 65 %	65 - 70 %	65 - 70 %

OLSON(22)

FIG. 19

BALL MILL DISCHARGE ARRANGEMENTS



	OVERFLOW	DIAPHRAGM	COMPARTMENTED
PROCESS	WET ONLY	WET OR DRY	WET OR DRY
CIRCUIT	USUALLY CLOSED	CLOSED	OPEN OR CLOSED
TYPICAL GRINDS	FINE (200 MESH)	INTERMEDIATE (WET) (65-100 MESH) FINE (DRY -325 MESH)	FINE (150-325 MESH)
MAX. FEED	10-14 MESH	MINUS ½"	MINUS ½"
L/D RATIO	1-1.5:1	1-1.5:1	OPEN 3.5-50:1 CLOSED 2.5-3.5:1
TYPICAL SPEEDS (% CRITICAL)	65-70 %	68-78 %	WET 65-75 % DRY 70-78 %
MEDIA - % VOLUME	40-45 %	35-50 %	30-50 %

OLSON(22)

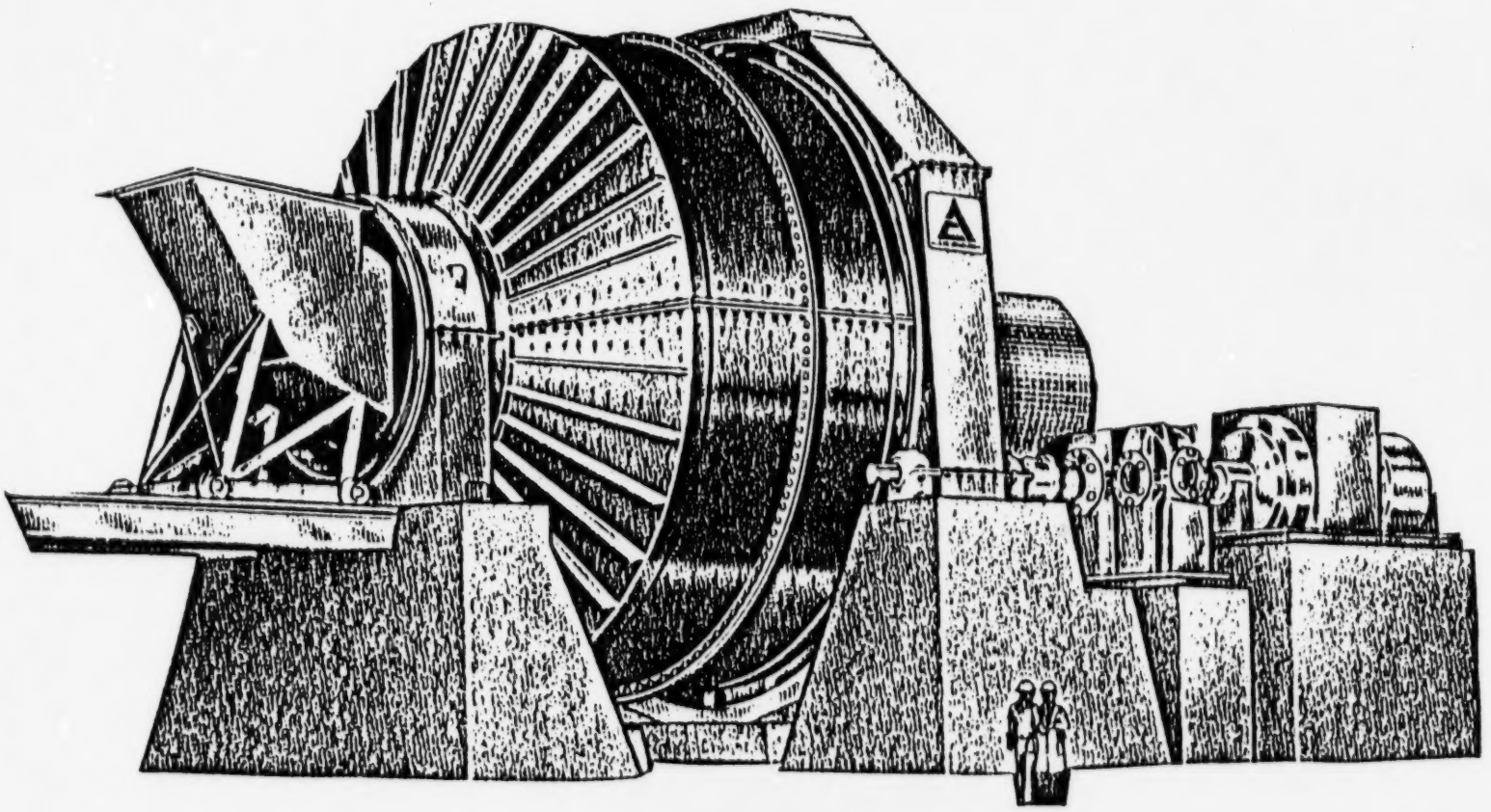


FIG. 20 ROCKCYL AUTOGENOUS GRINDING MILL -12,000 HP-

OLSON(22)

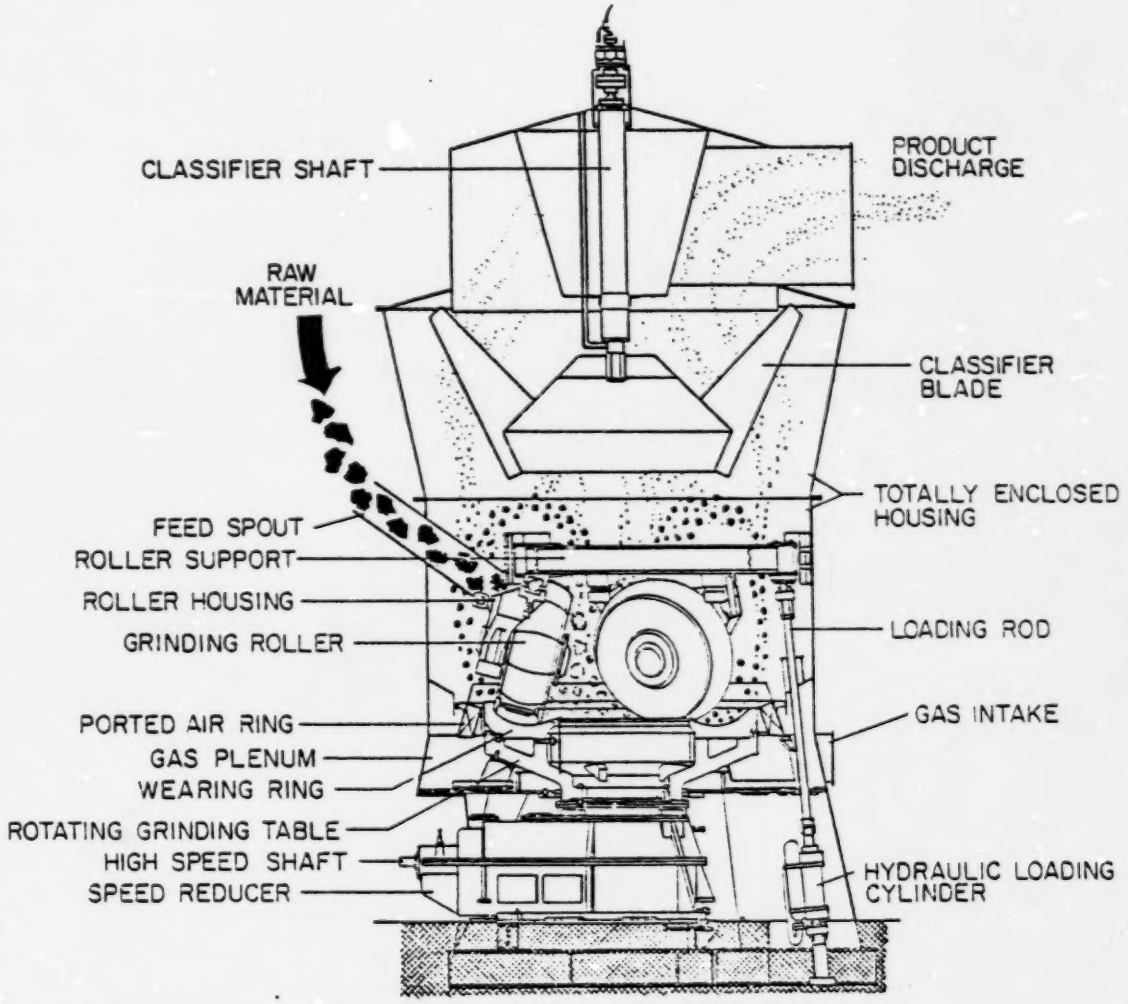


FIG. 21 ROLLER MILL

OLSON(22)

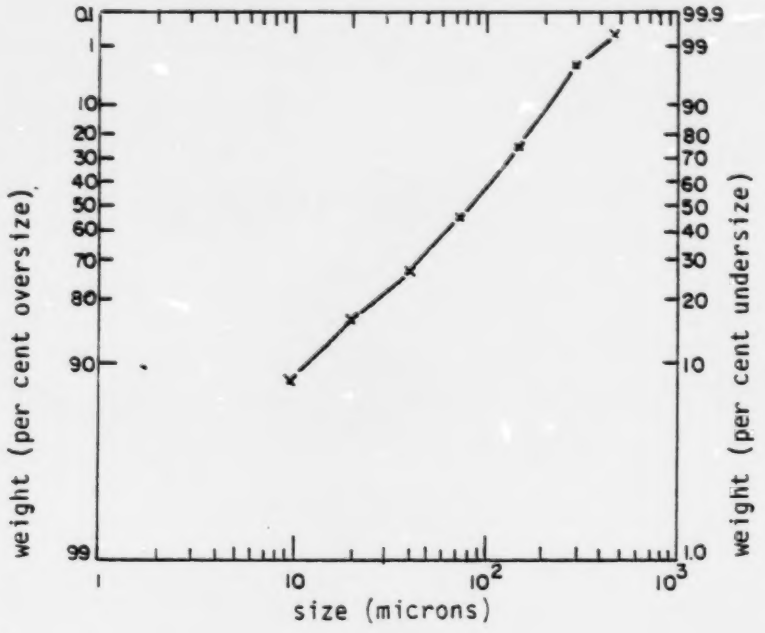


FIG. 22-1 TYPICAL PRODUCT SIZE DISTRIBUTION FOR AUTOGENOUS MILL CRUSHING LIMESTONE

STAIRMAND(28)

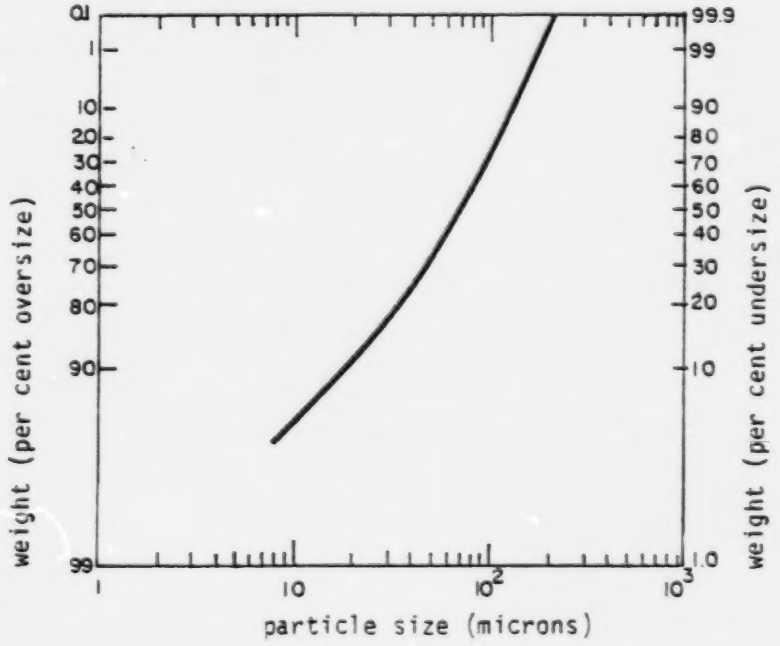
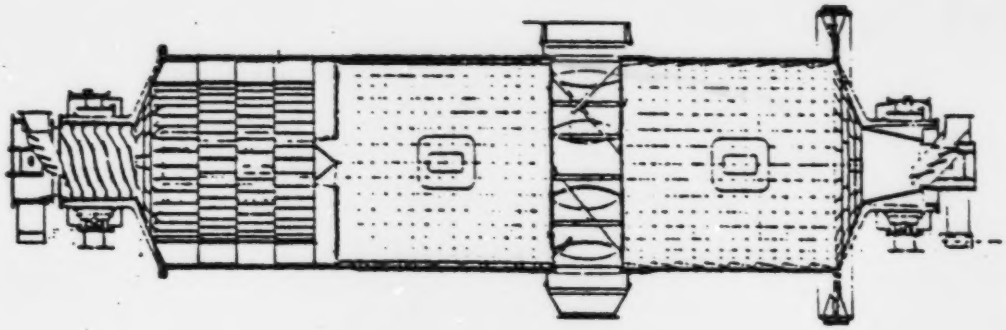


FIG. 22-2 TYPICAL PRODUCT SIZE DISTRIBUTION FOR A BALL MILL CRUSHING LIMESTONE

STAIRMAND(28)



DOUBLE ROTATOR MILL

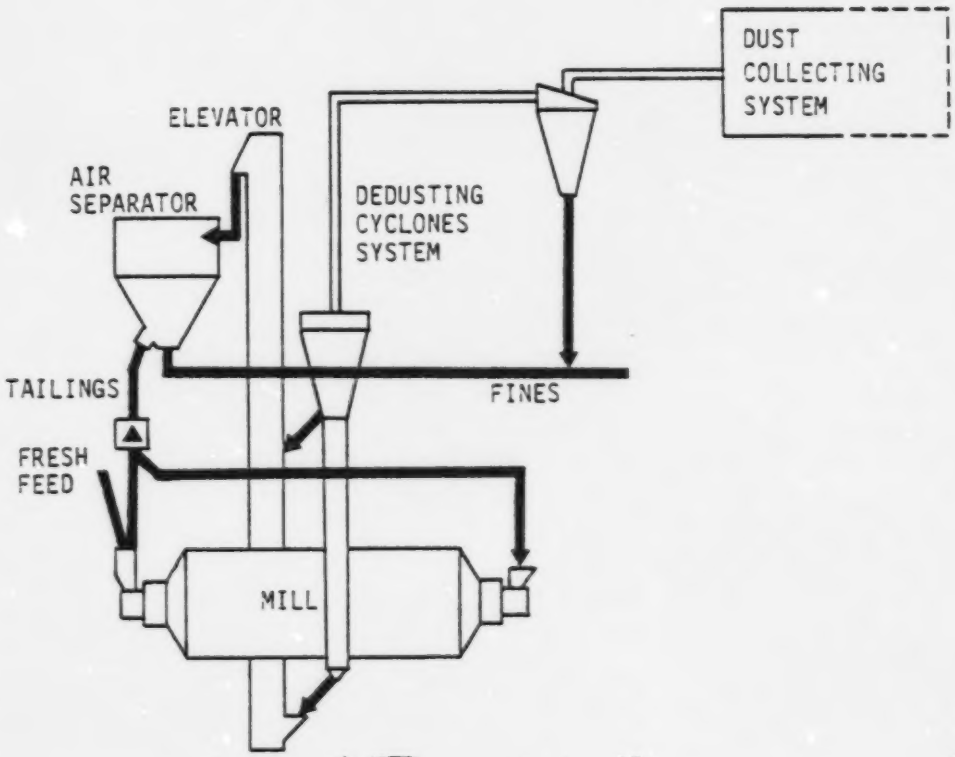


FIG. 23 DOUBLE ROTATOR MILL SYSTEM

OLSON (22)

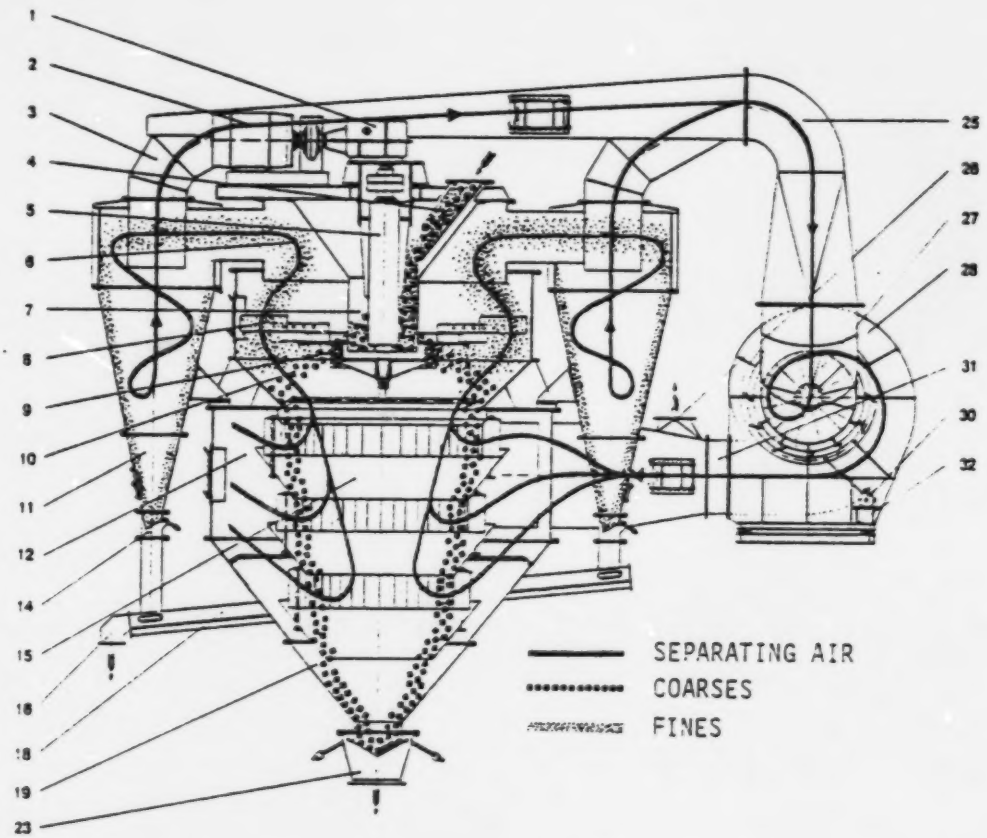


FIG. 24 AIR SEPARATOR (WEDAG)

1 Reduction gear
2 Motor
3 Air collecting duct
4 Feed spout
5 Bearing support
6 Exhaust head
7 Lower feed pipe
8 Auxiliary fan (centrifugal system)
9 Distribution plate
10 Separating zone (upper housing)
11 Cyclones
12 Center housing
14 Gravity operated flap gate for fines
15 Return air vanes
16 Fines discharge spout
18 Air trough conveyor for fines
19 Tailings cone (lower housing)
23 Gravity operated flap gate for coarses
25 Separator air duct
26 Duct to dust collector
27 Damper or control of blower vanes
28 Blower
30 Vane control arrangement
31 Expansion joint
32 Base frame

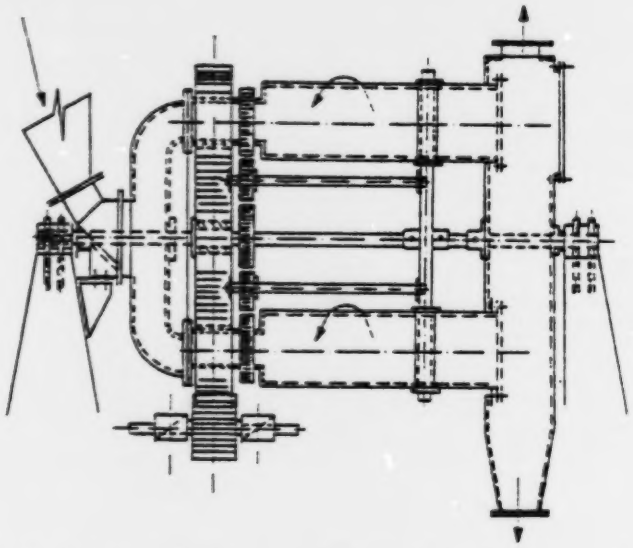


FIG. 25-1 DIAGRAMMATIC SKETCH OF A PLANETARY BALL MILL FOR DRY GRINDING

DUDA(5)

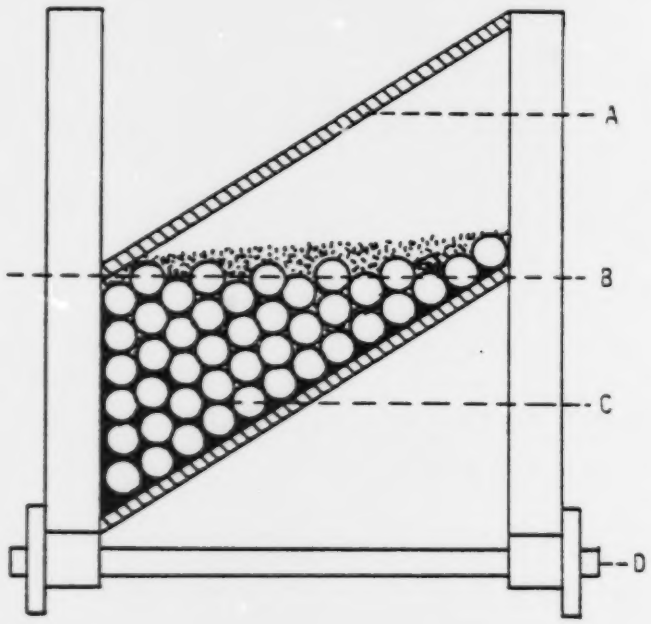


FIG. 25-2 SLANT MILL

A- INCLINED MILL BARREL
B- HORIZONTAL AXIS OF ROTATION
C- MEDIA LOAD
D- SUPPORTING ROLLERS

VIVIAN(31)

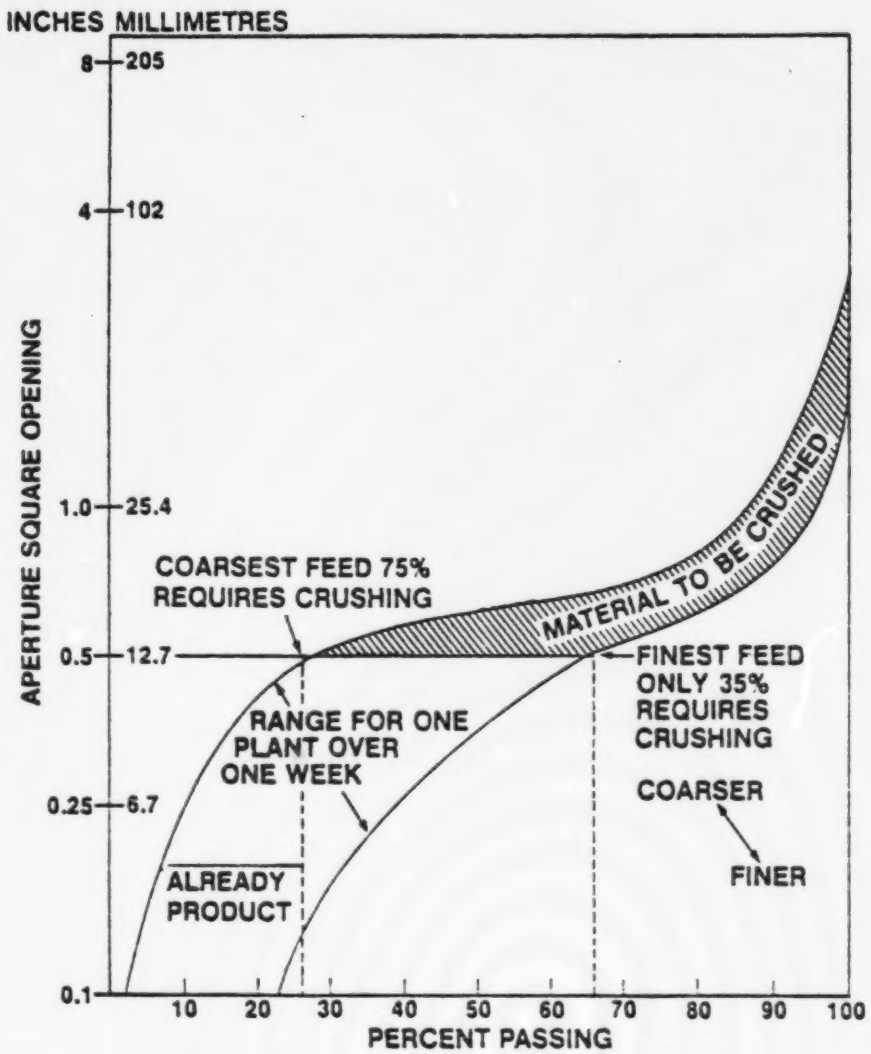


FIG. 26 EXAMPLE OF FEED SIZE DISTRIBUTION
RELATED TO AMOUNT OF CRUSHING REQUIRED

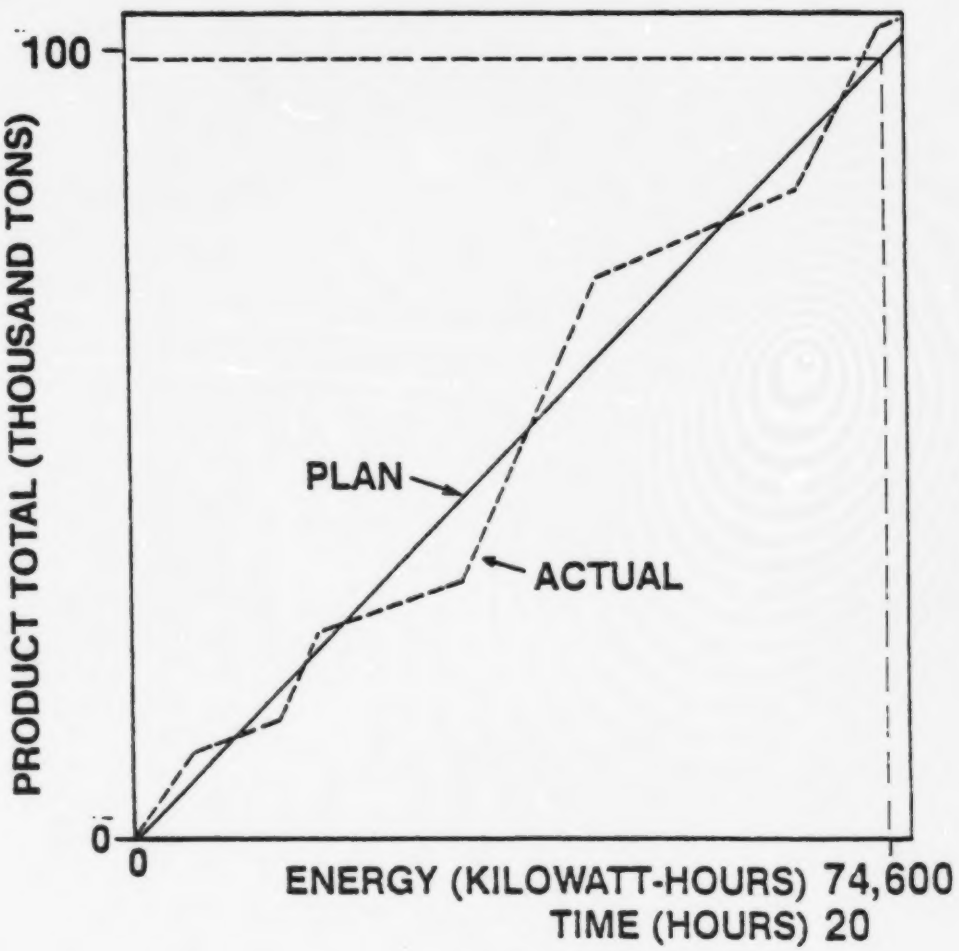


FIG. 27 AUTOMATED CRUSHING PLANT CONTROL SHOWING PLANNED AND ACTUAL POWER PER UNIT OF FEED

FLAVEL(7)

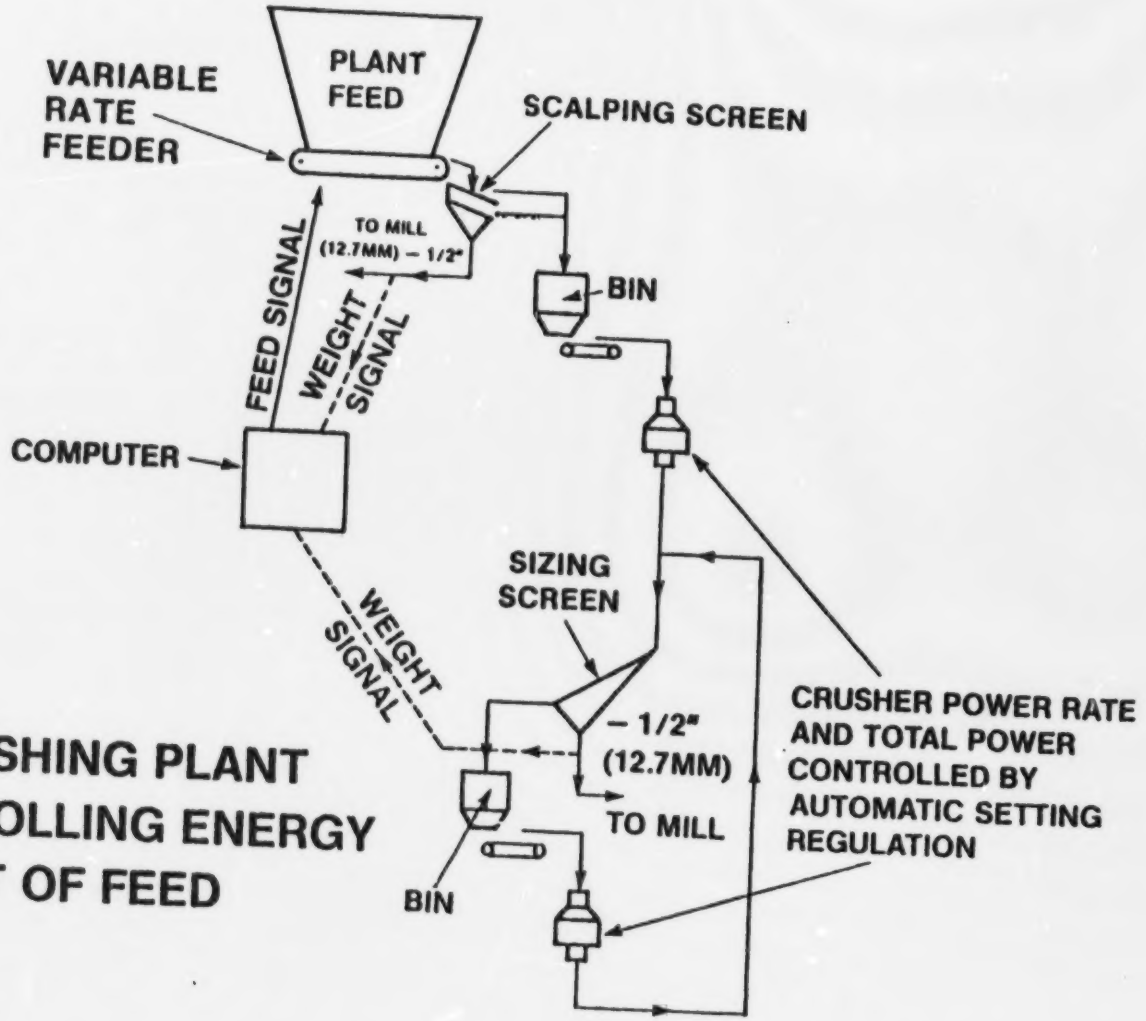


FIG. 28

AUTOMATED CRUSHING PLANT CONCEPT CONTROLLING ENERGY APPLIED PER UNIT OF FEED

FLAVEL(7)

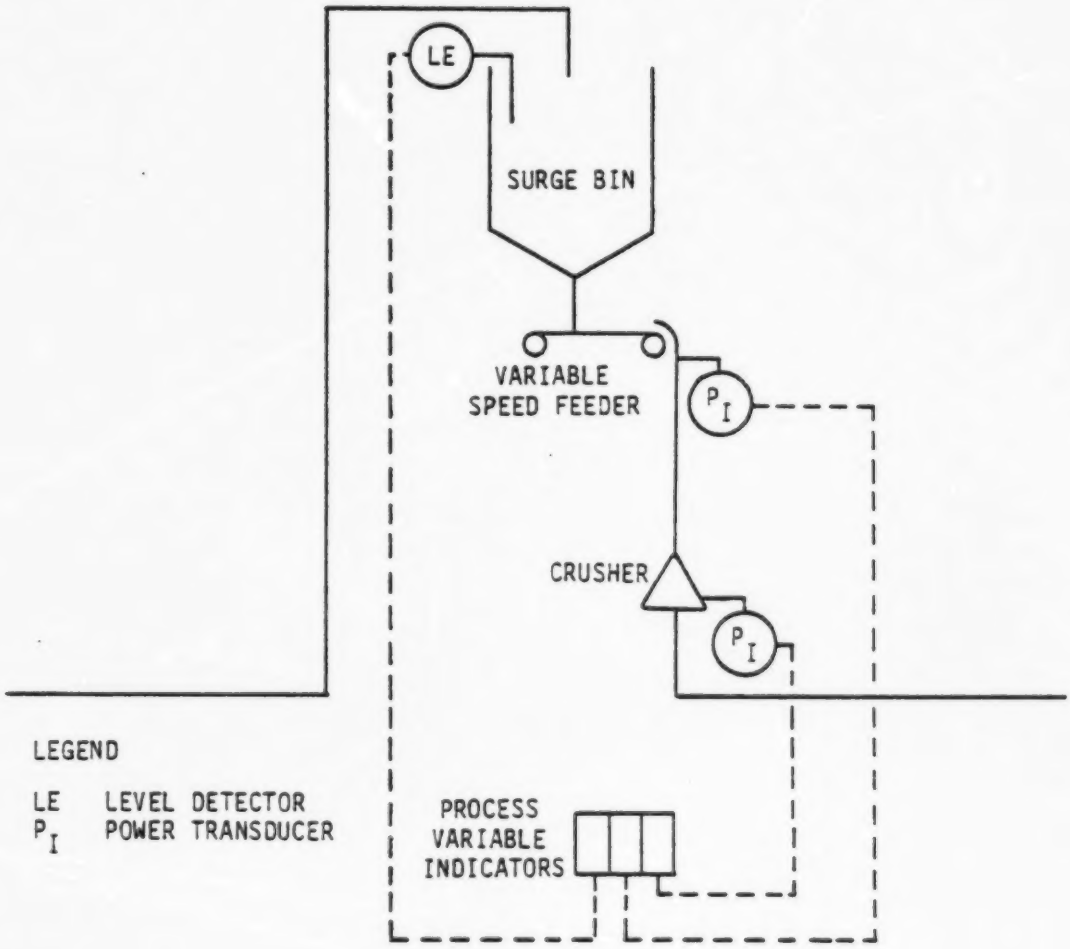
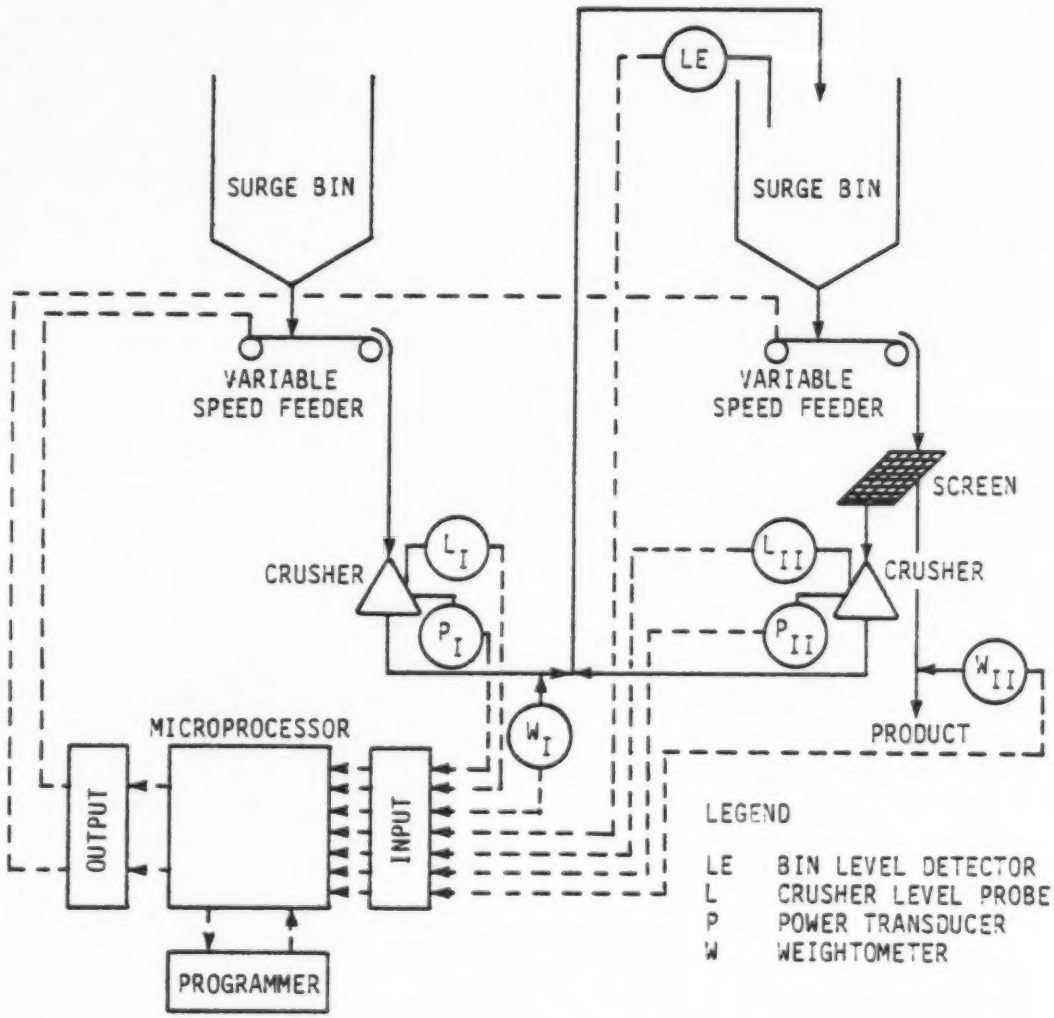


FIG. 29-1 SIMPLE OPEN CIRCUIT CRUSHER CONTROL FOR MAINTAINING POWER DRAW

L.MOLLICK(20)

FIG. 29-2 "SMART" CONTROL FOR CRUSHER BASED ON MICROPROCESSOR



L. MOLLICK (20)

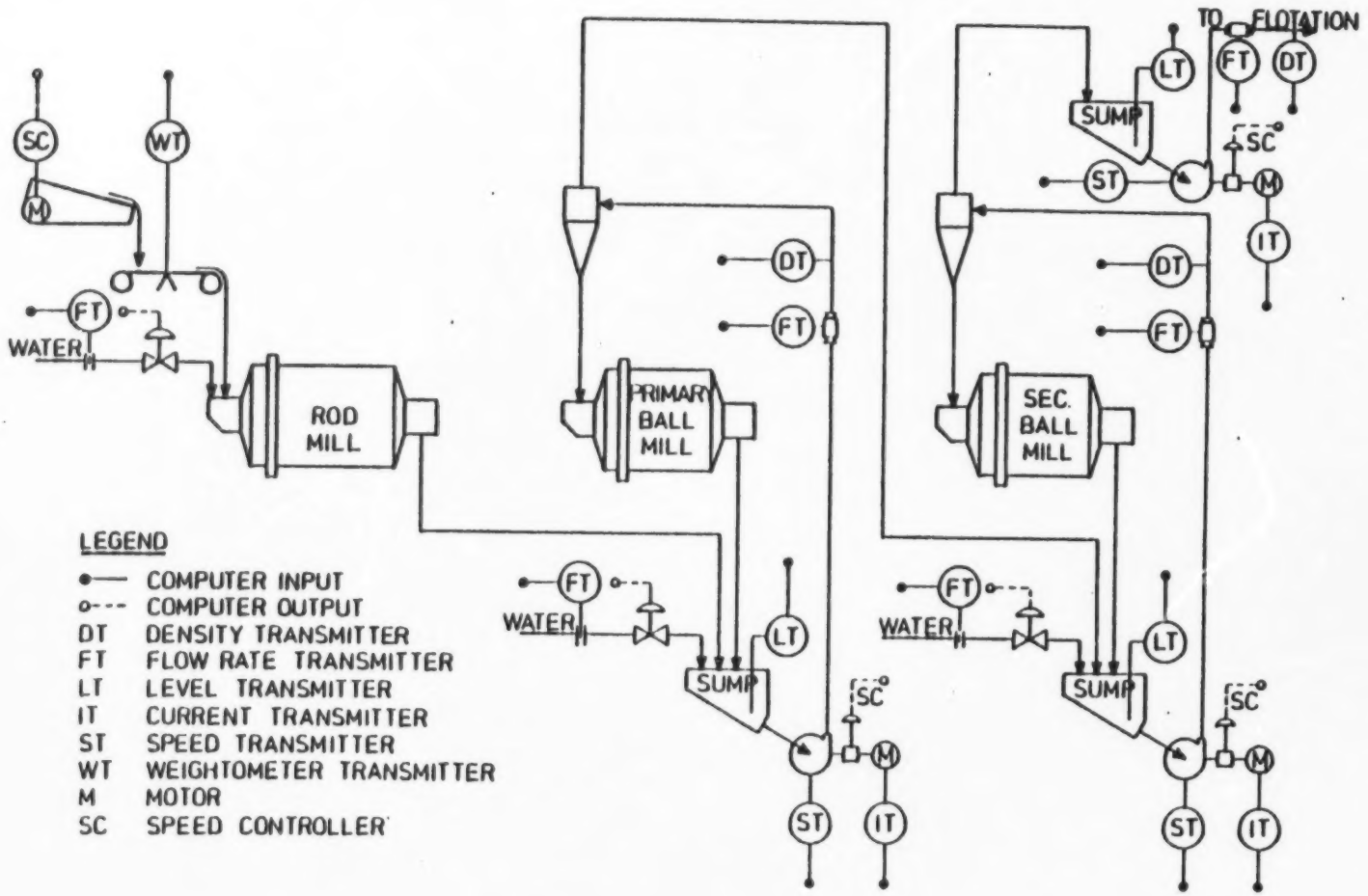


FIG. 30 MULTISTAGE WET GRINDING CONTROL

LYNCH (14-18)

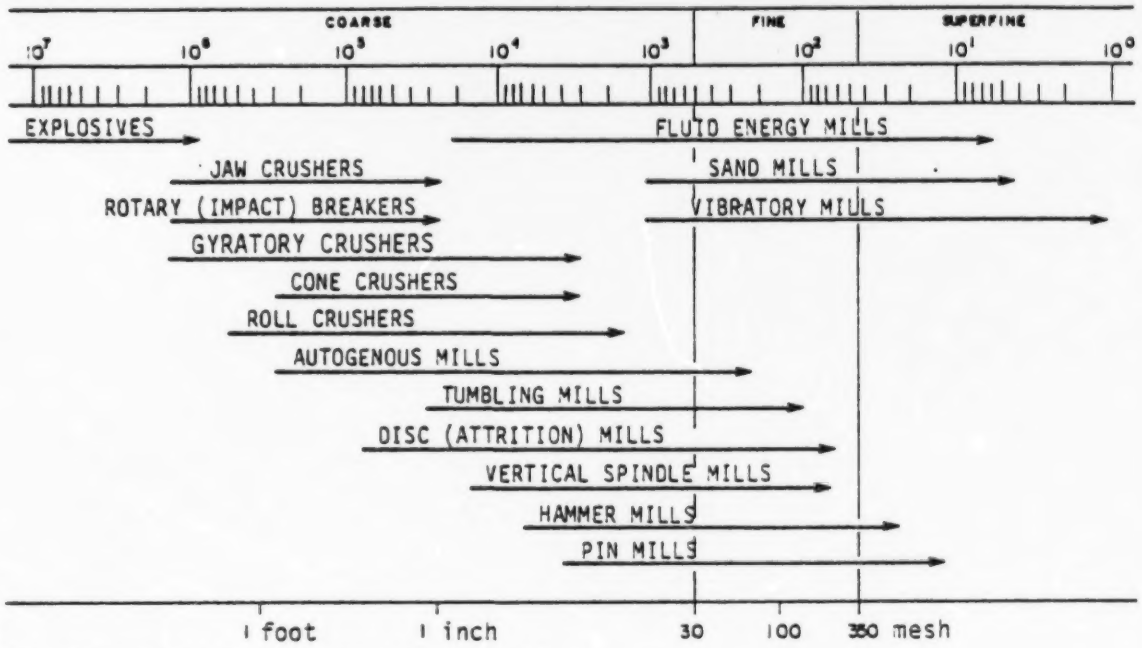


FIG. 31 RANGE OF OPERATION OF MACHINES

NOTES (1) THE SIZE QUOTED IS "80% PASSING" SIZE

(2) THE RANGE QUOTED IS FROM MAXIMUM FEED SIZE ACCEPTED BY THE PARTICULAR TYPE OF MACHINE TO MINIMUM PRODUCT SIZE PRODUCED BY THE PARTICULAR TYPE OF MACHINE

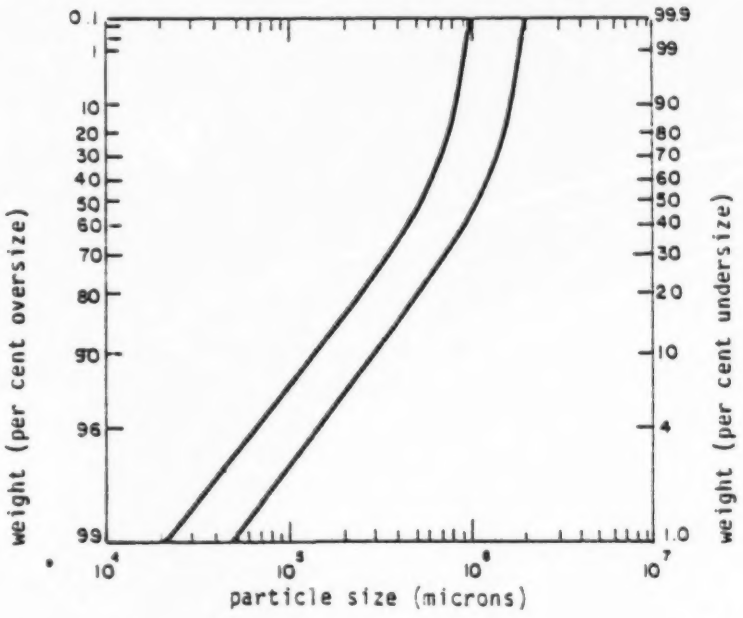


FIG. 32 PRODUCT SIZE DISTRIBUTION FROM PRIMARY BLASTING OF SEDIMENTARY ROCKS

STAIRMAND(28)

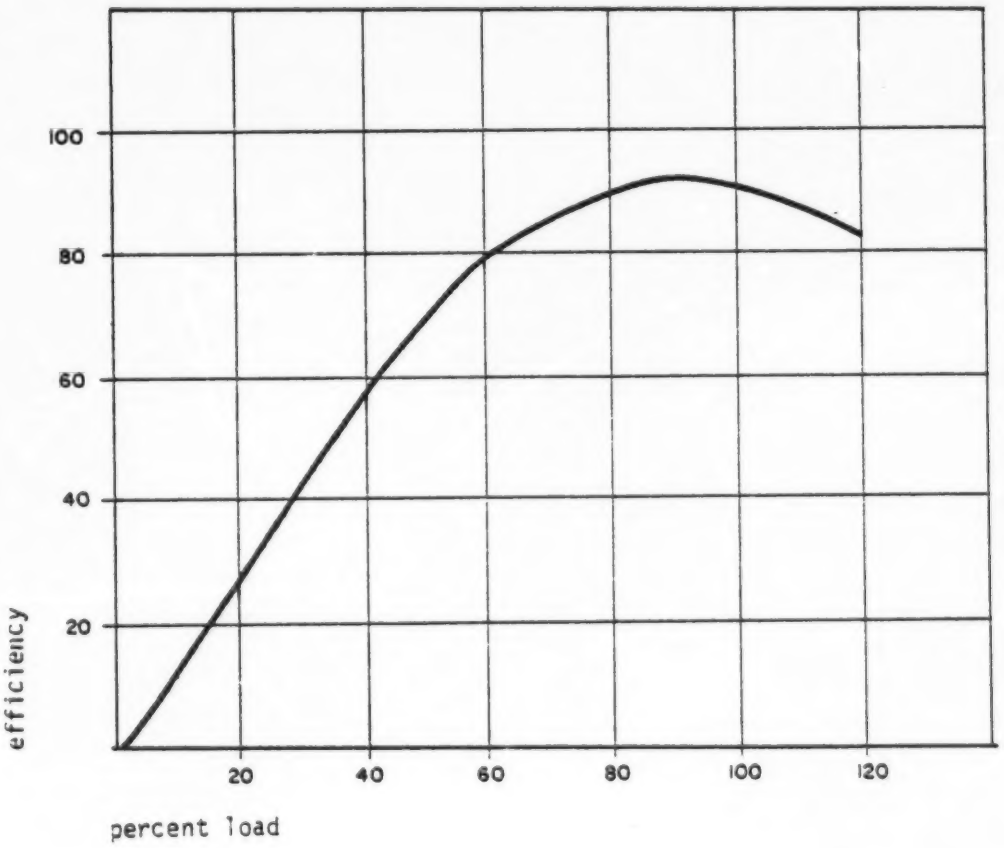


FIG. 33 TYPICAL EFFICIENCY VARIATIONS FOR GENERAL PURPOSE INDUCTION MOTORS

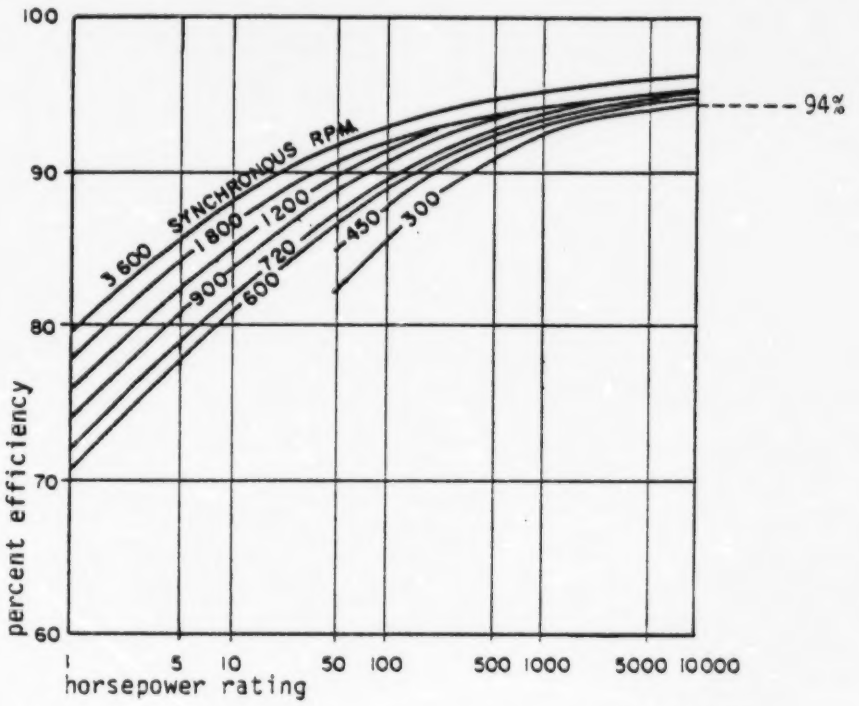


FIG. 34 TYPICAL FULL-LOAD EFFICIENCIES FOR NORMAL-TORQUE LOW-STARTING-CURRENT POLYPHASE INDUCTION MOTORS

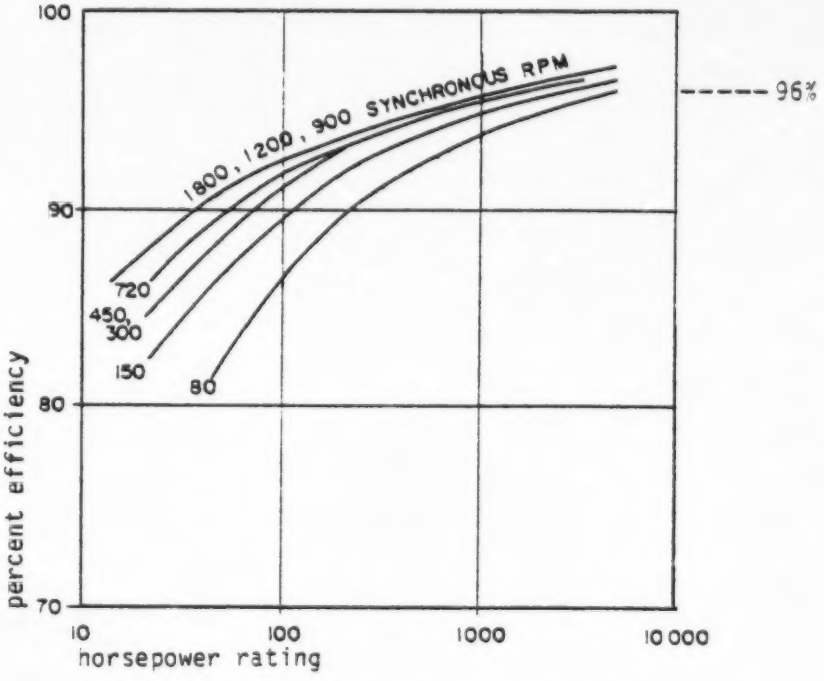
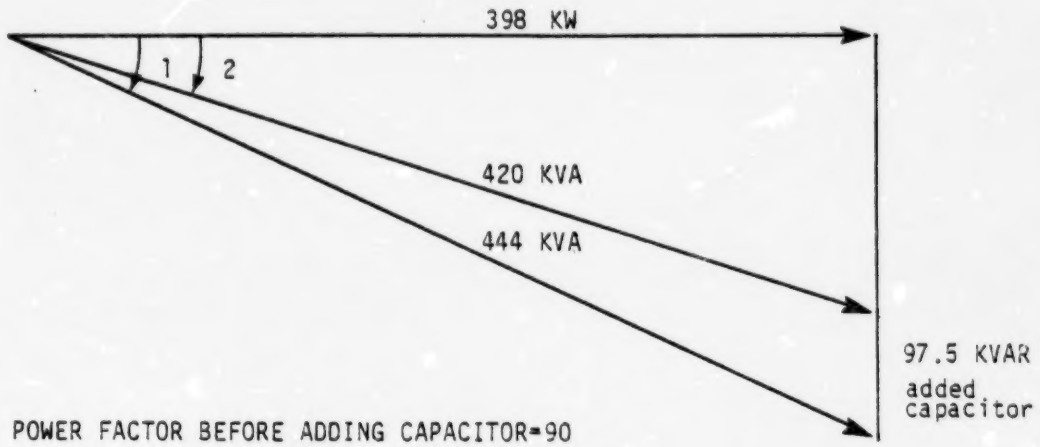


FIG. 35 TYPICAL FULL-LOAD EFFICIENCIES FOR 1.0-POWER-FACTOR DC-EXCITED SYNCHRONOUS MOTORS



1 POWER FACTOR BEFORE ADDING CAPACITOR=90

2 POWER FACTOR AFTER ADDING CAPACITOR = 97

FIG.36 THE KVA DECREASE IS 24 KVA WHICH IN FACT REPRESENTS A GAINED SPARE CAPACITY OF 24 KVA

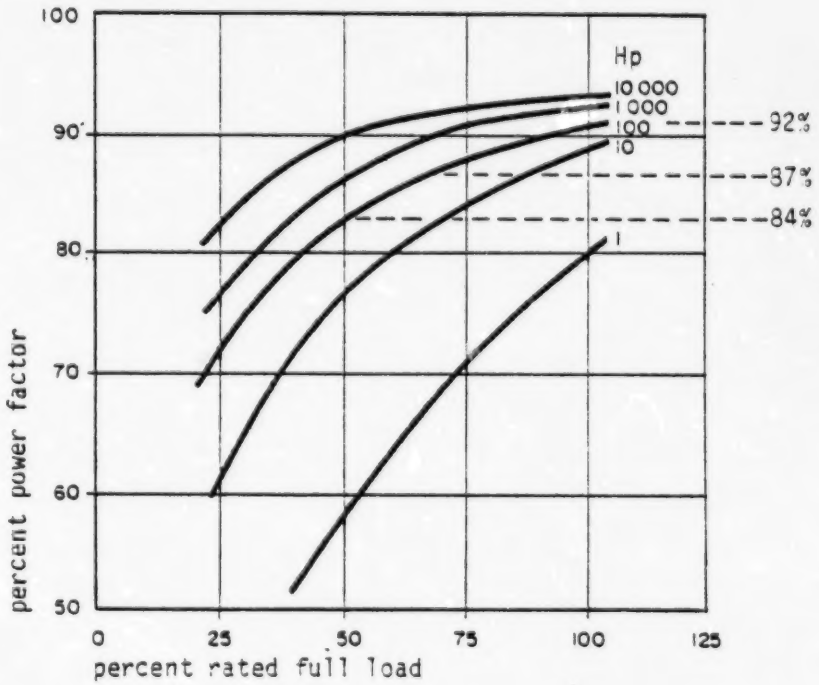


FIG. 37 TYPICAL POWER-FACTOR CURVES FOR 1,800 -RPM NORMAL-TORQUE LOW-STARTING-CURRENT POLYPHASE INDUCTION MOTORS. POWER FACTOR OF MOTOR DROPS AT REDUCED LOADS

CEMENT-MANUFACTURING

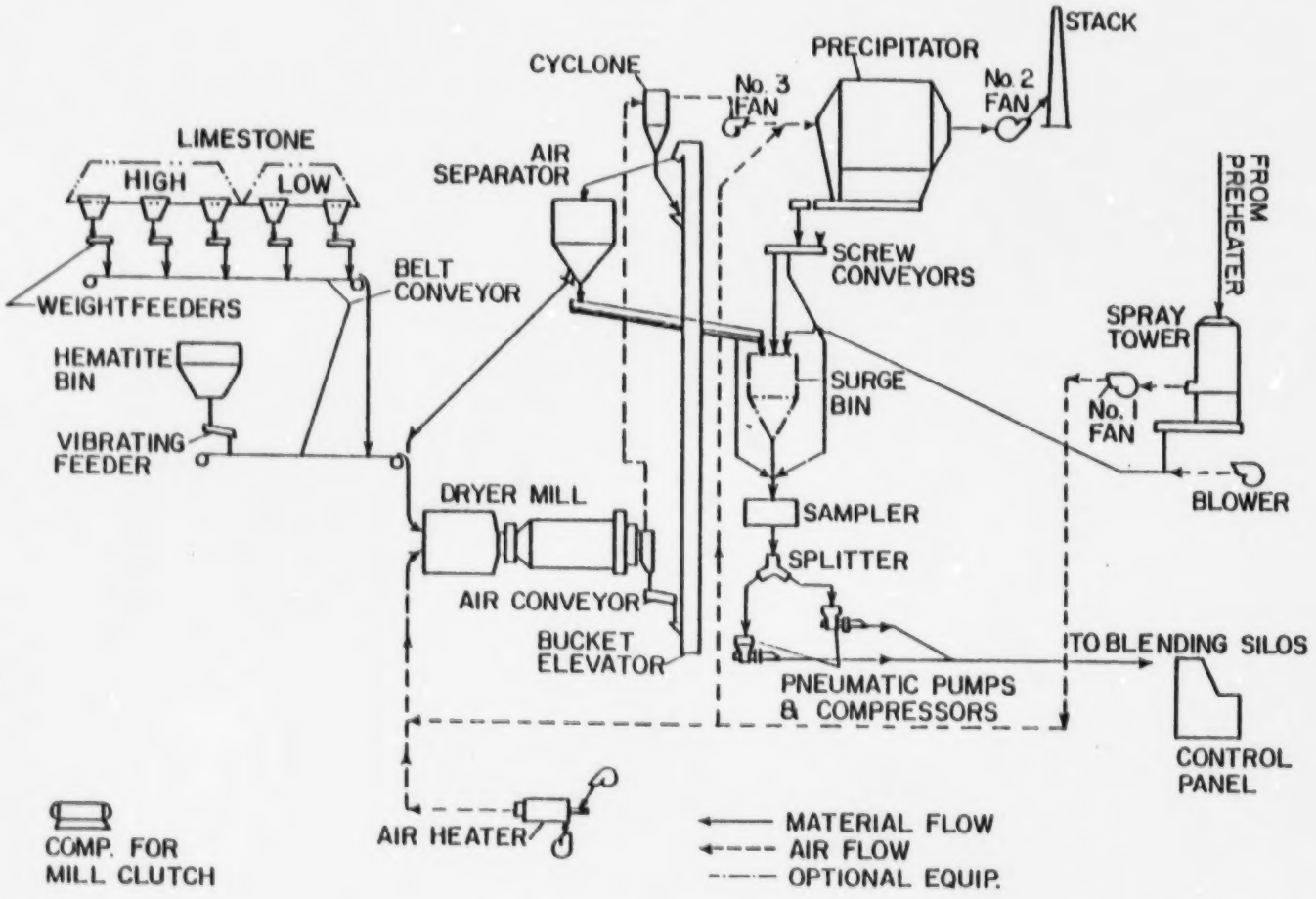


FIG. 38 DRYER MILL

OLSON(22)

CEMENT-MANUFACTURING

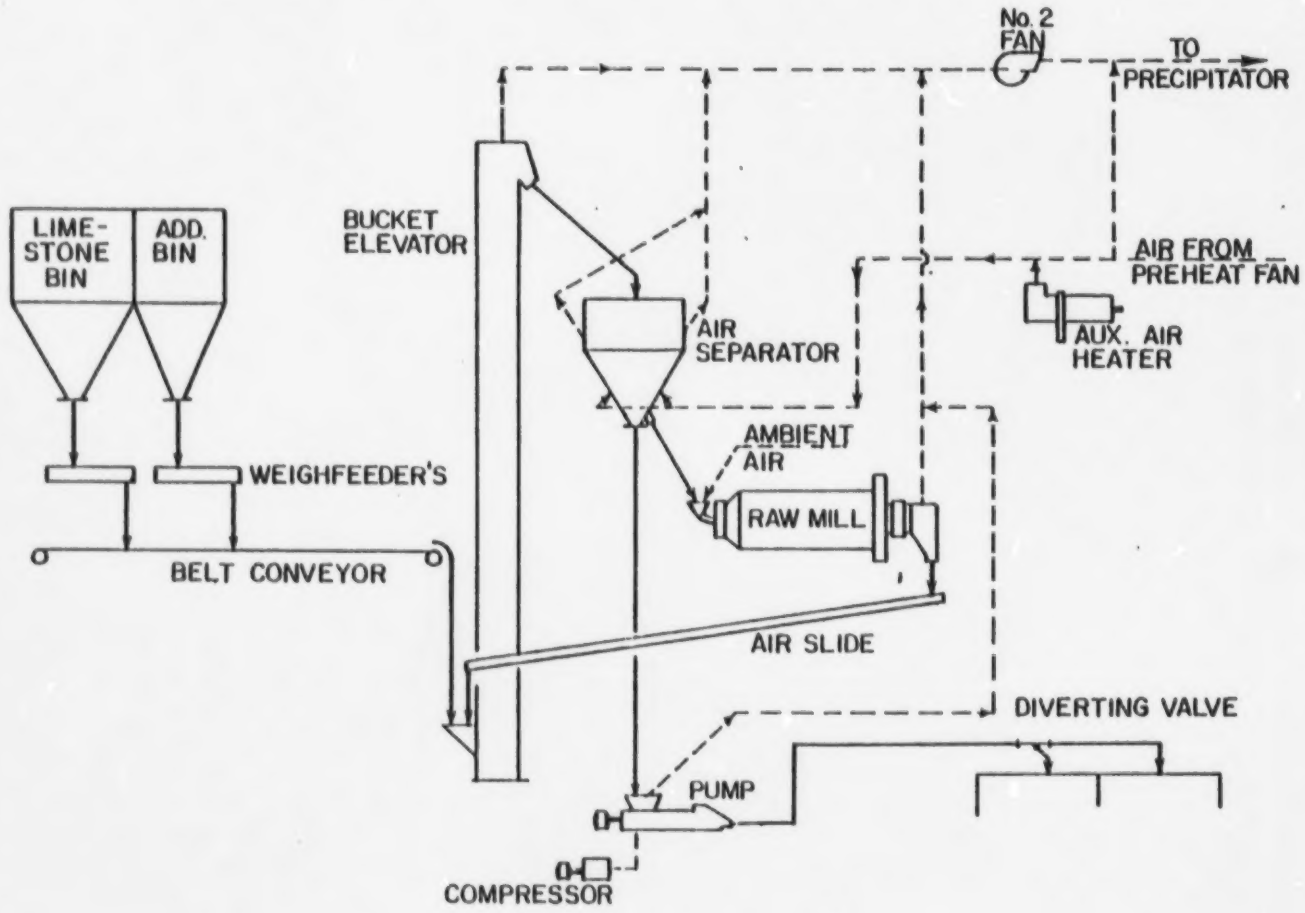


FIG. 39 RAW GRINDING

OLSON(22)

CEMENT-MANUFACTURING

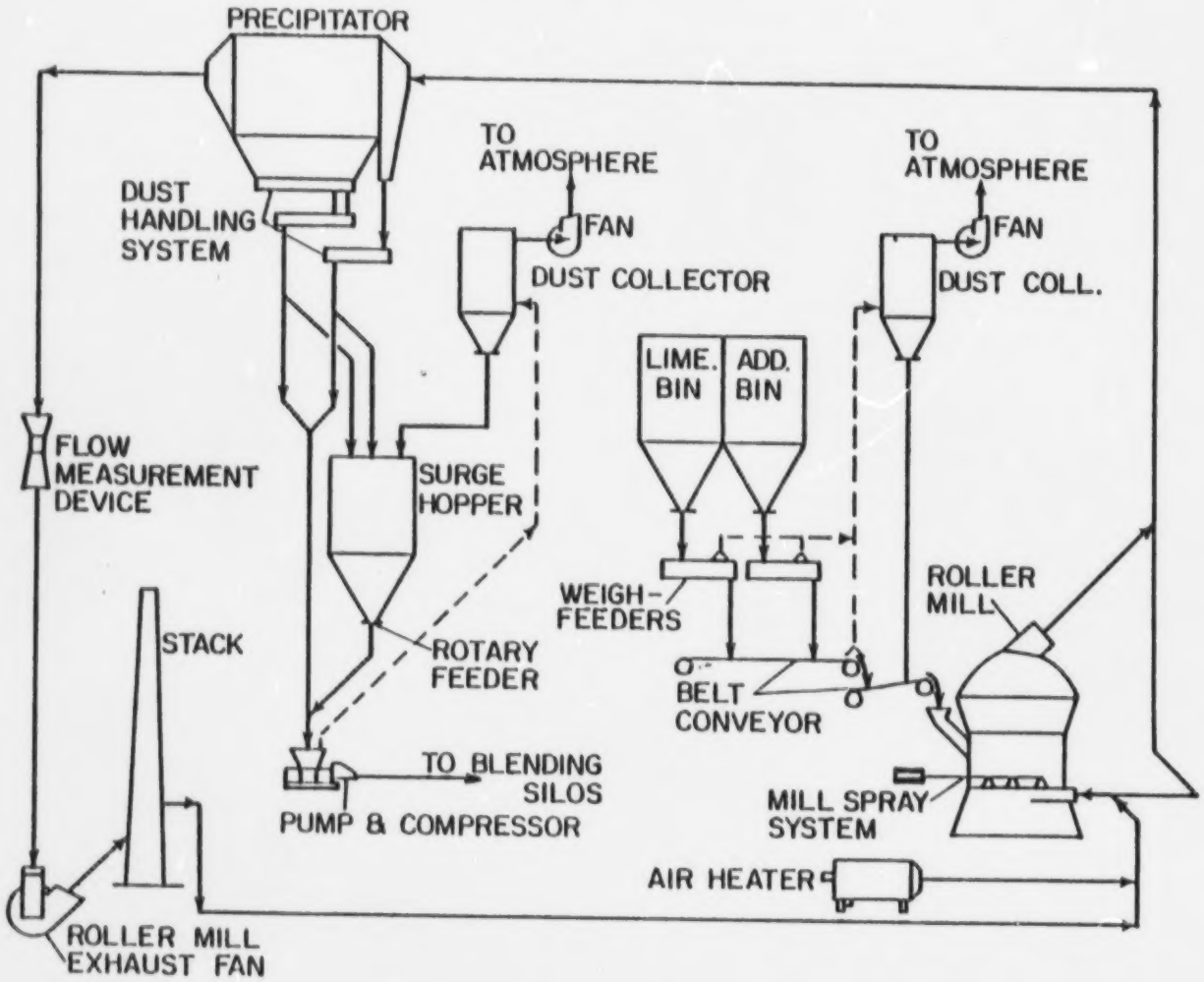


FIG. 40 ROLLER MILL CIRCUIT

OLSON(22)

CEMENT MANUFACTURING

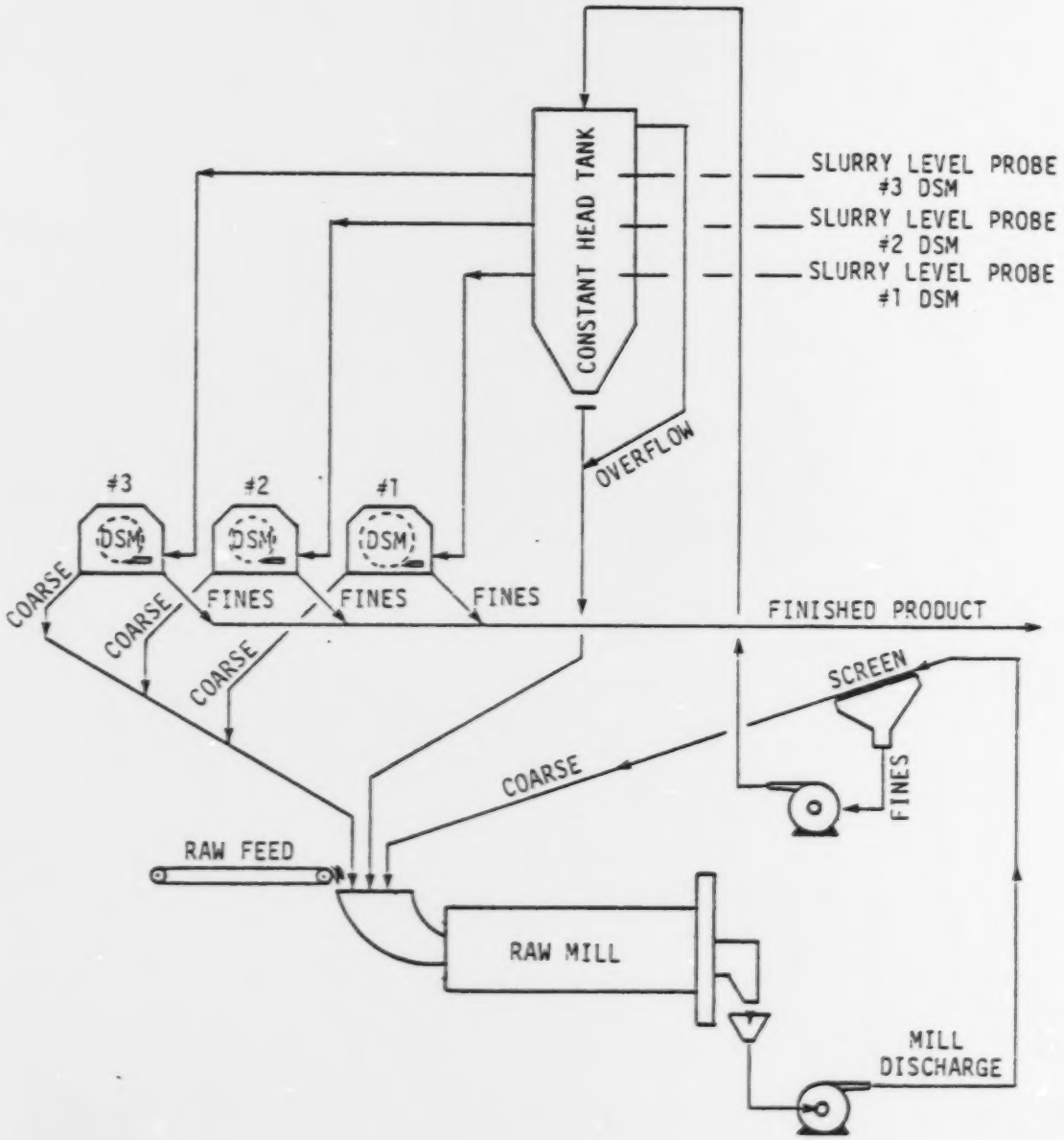


FIG. 41 WET RAW GRINDING

LESNIAK(17)

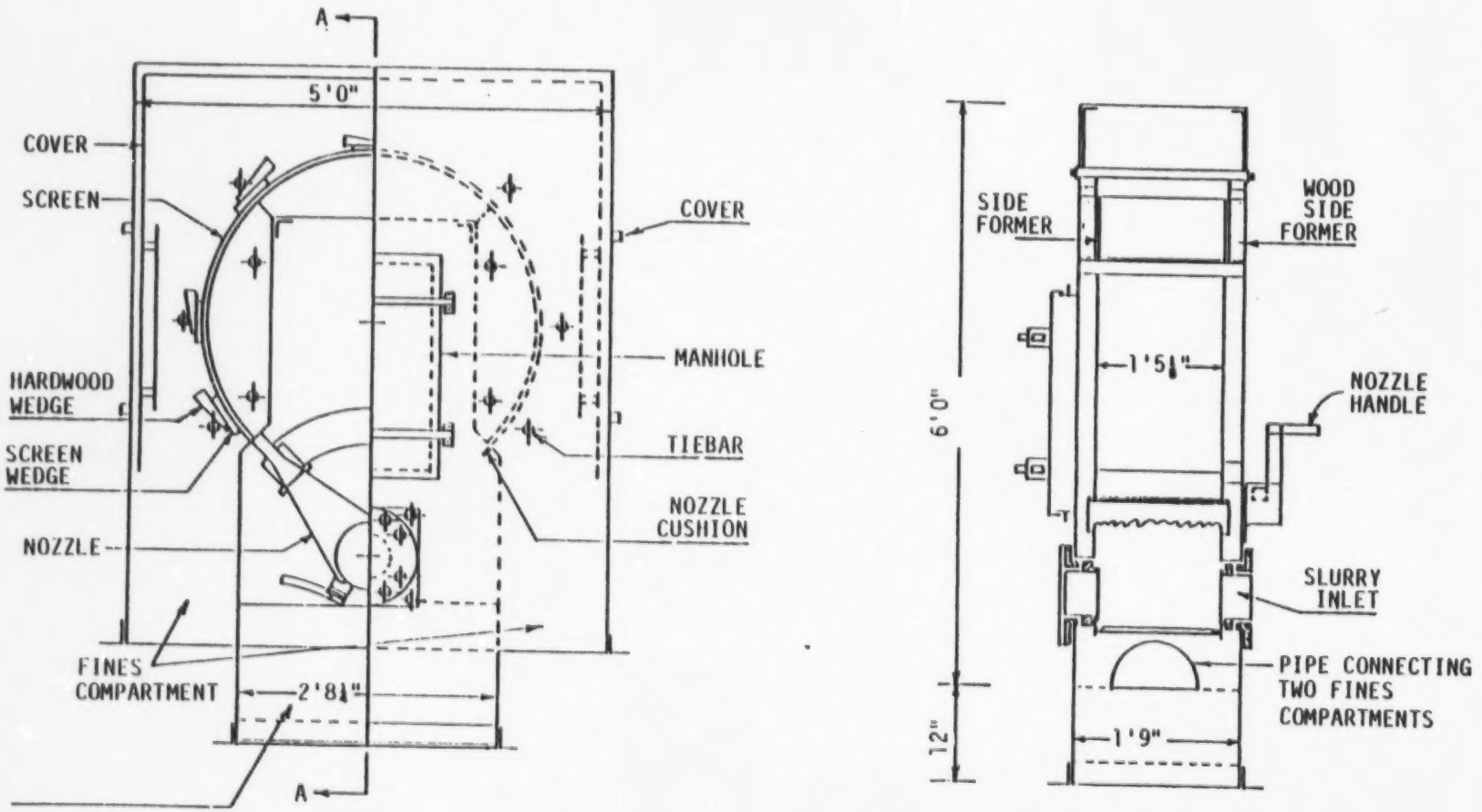


FIG. 42 D.S.M. SCREEN

LESNIAK(17)

CEMENT MANUFACTURING

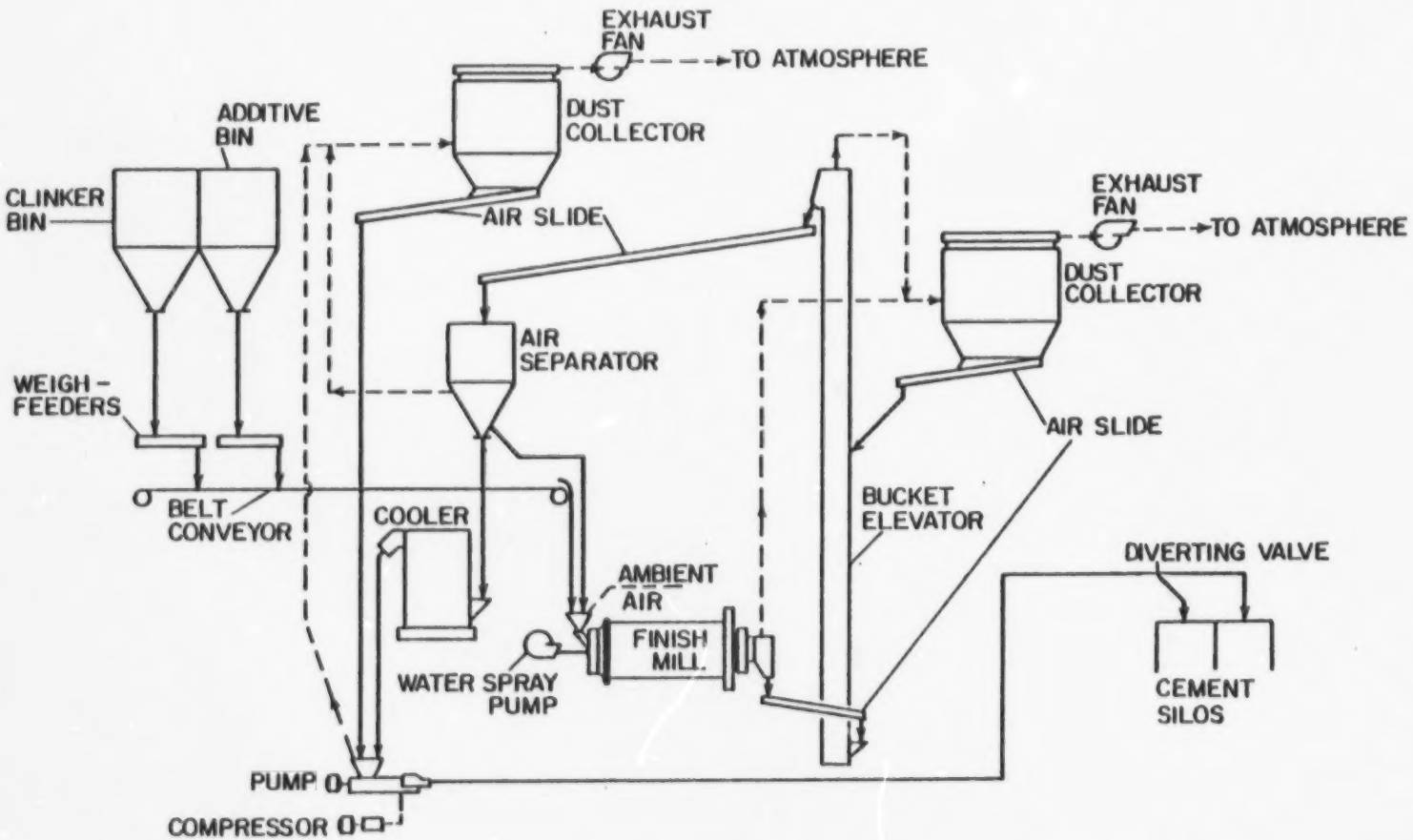


FIG. 43 CEMENT GRINDING

OLSON(22)

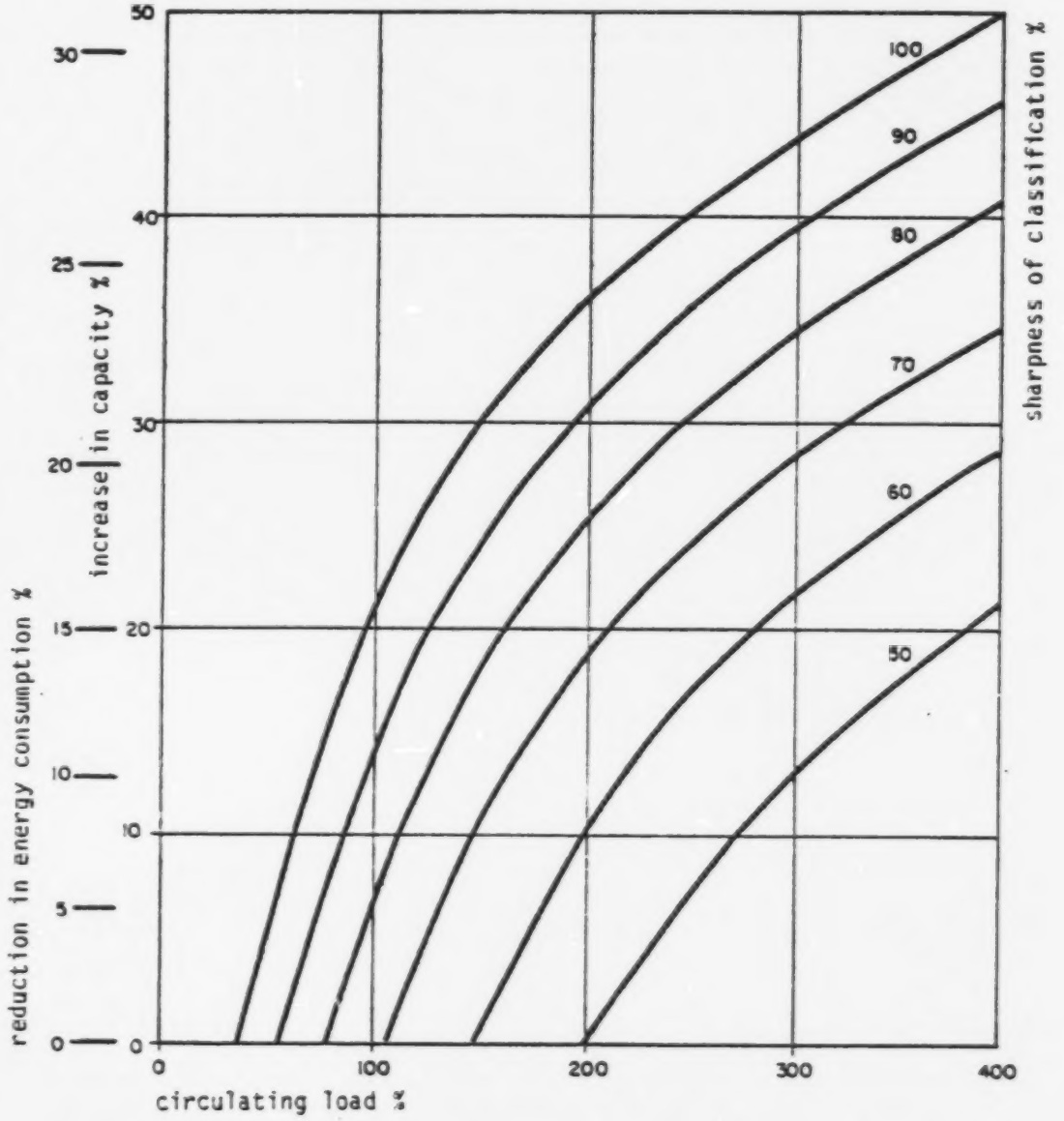


FIG. 44 EXPERIMENTAL CURVES SHOWING THE FUNDAMENTAL RELATIONSHIP BETWEEN CIRCULATING LOAD, SHARPNESS OF CLASSIFICATION, INCREASE IN CAPACITY AND REDUCTION IN ENERGY CONSUMPTION IN CLOSED GRINDING CIRCUITS

"SHARPNESS IN CLASSIFICATION" INDICATES THE RECOVERY OF - X MICRONS MATERIAL INTO THE PRODUCT FINE PRODUCT

HUKKI(15)

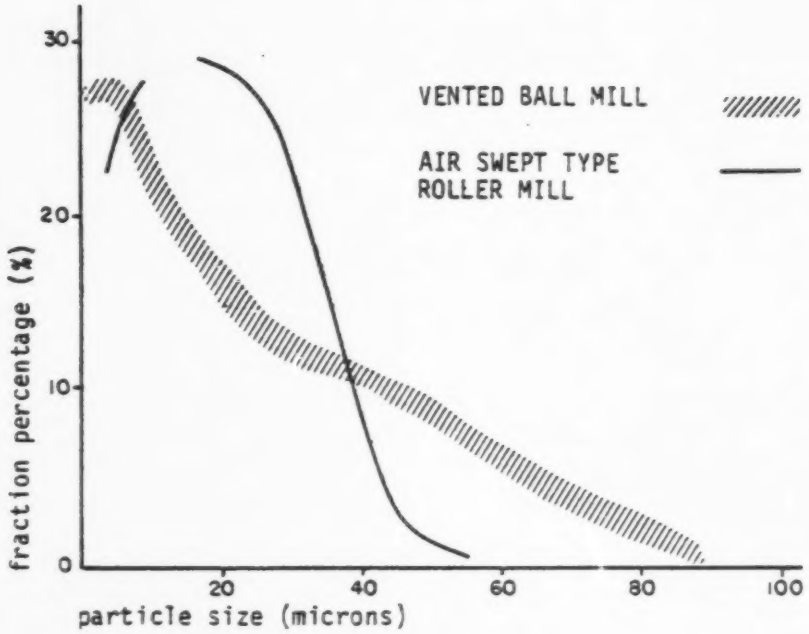


FIG. 45 -1 PARTICLE SIZE DISTRIBUTION
(BALL MILL VS ROLLER MILL)

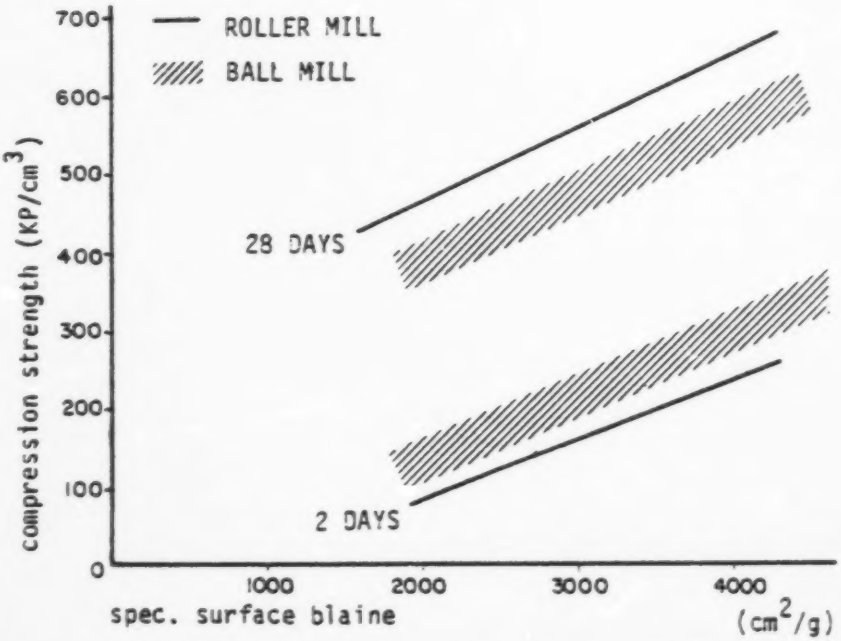
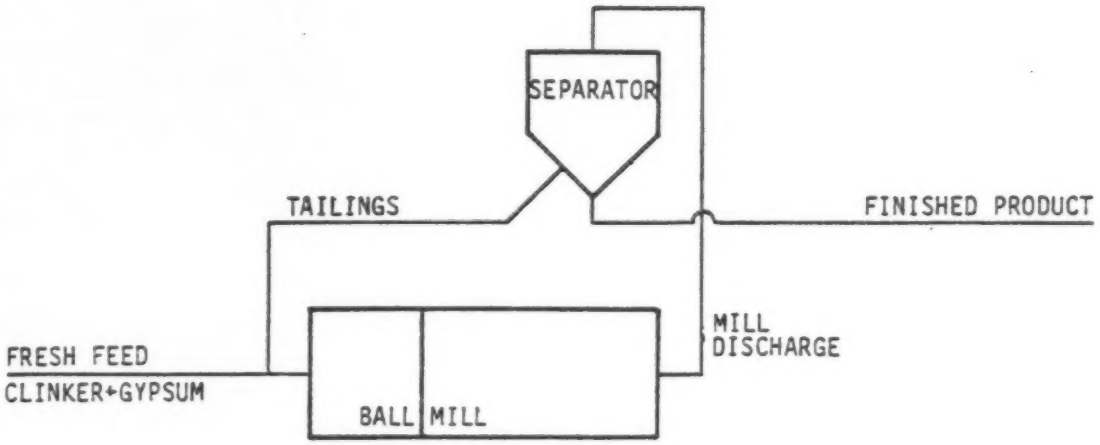


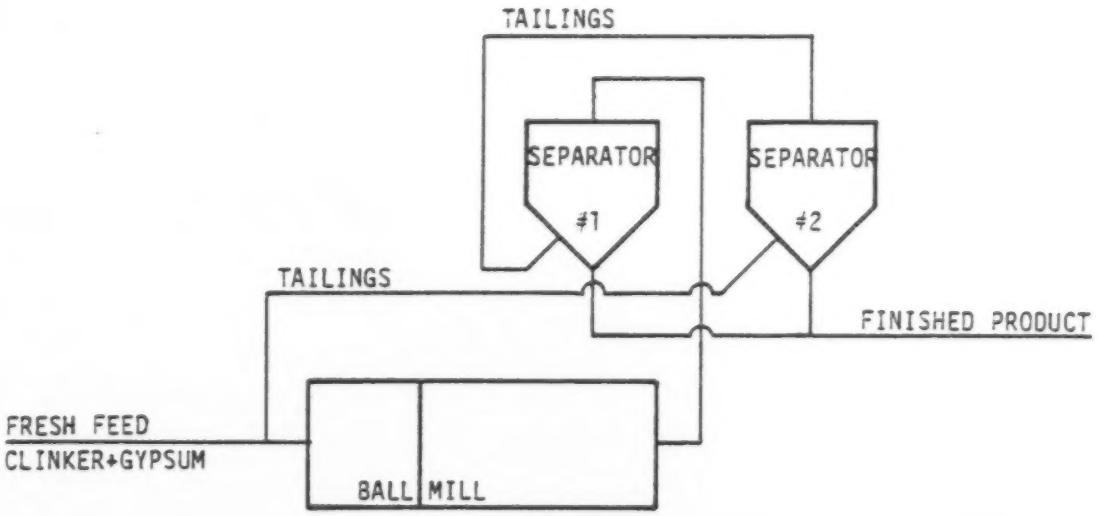
FIG. 45 -2 THE RELATIONSHIP OF COMPRESSIVE STRENGTH
TO SPECIFIC SURFACE AREA

SCHWEINDIG(26)

CEMENT MANUFACTURING



CONVENTIONAL CLOSED-CIRCUIT GRINDING



CLOSED CIRCUIT GRINDING WITH TWO SEPARATORS IN SERIES

FIG. 46 CEMENT GRINDING ARRANGEMENTS